GROWTH EFFICIENCY OF DUST AGGREGATES THROUGH COLLISIONS WITH A GREAT DIFFERENCE IN THEIR SIZES.

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Introduction: In protoplanetary disks planetesimals are believed to be formed from dust aggregates consisting of submicron grains, but their growth process is unclear so far. 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]. Recently, we have 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, both of which are fluffy and thought to well represent the dust structures. As a result, we find that fluffy aggregates represented by BPCA clusters are able to grow at collision velocities up to ~ 50 m/s if they consist of ice particles [2]. On the other hand, the critical collision velocity for aggregates consisting of silicate particles is given by ~ 5 m/s, based on an energy scaling [2]. If this is the case, silicate dust could not grow through collisions in protoplanetary disks. These results are, however, obtained through collisions of equal-sized aggregates. Collisions between different-sized aggregates may increase the critical velocity since such colliding aggregates are expected to stop and stick more easily than at equal-sized collisions. In this study, we carry out numerical simulations of collisions between BPCA clusters with various mass ratios to clarify the effect of collisions of different-sized aggregates on the critical collision velocity. Based on the numerical results, we discuss the feasibility of planetesimal formation through collisions of dust aggregates in protoplanetary disks.

Numerical model and settings: We performed 3D simulations of aggregate collisions by the use of the particle interaction model and the numerical code developed in the previous papers [3, 4]. 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 because of 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 two sorts of aggregates: projectiles and targets, both of which are BPCA clusters but projectiles are much smaller than targets. The number of particles consisting of projectiles, N_{proj}, is 500, 2000, or 8000, while that of targets, N_{target}, is 8000, 32000, 128000, or 512000. We use these aggregates with the size ratios N_{target}/N_{proj} = 1, 16, or 64 (see Fig. 1, for example) to examine the size and the size-ratio dependences on the collisional growth efficiency f defined by

$$f = (N_{large} - N_{target})/N_{proj} ,$$

where N_{large} is the number of particles of the largest remnant in a collision. The growth efficiency counts how many particles, normalized by N_{proj}, are gained (or lost, if the value is negative) for a target aggregate through a collision. We carry out the collision simulations with various values of the impact parameter b and the numerical results are averaged over b. Particles are all spheres with the same radius of 0.1 μm 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).

Results: As shown in Fig. 1, projectile aggregates are effectively captured by target aggregates even at high velocity (52 m/s) collisions. In addition, the energy dissipation region is not distributed over whole target aggregates, suggesting that the collisional influence is limited to a region near the impact site.

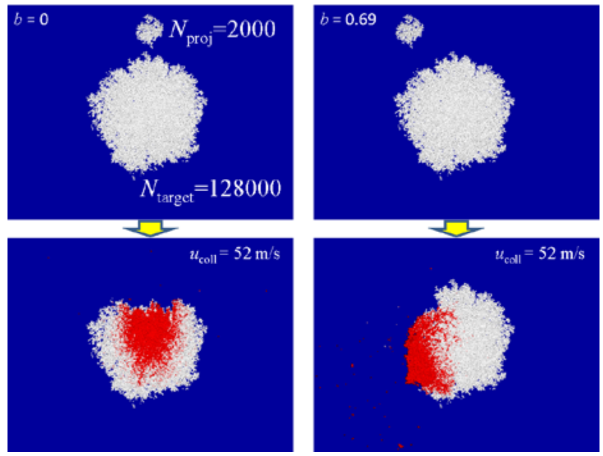

Figure 1: Examples of cross sectional views of initial ice aggregates with N_{proj} =2000 and N_{target} =128000 (upper panels) and their collisional outcomes (lower panels). The impact parameter b is set to 0 (left) and 0.69 (right). Red-colored particles show where energy dissipates. Collision velocity is 52 m/s for both cases.

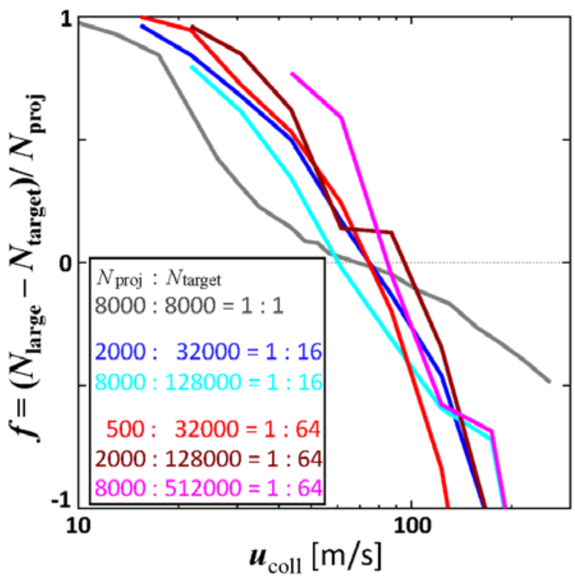

Figure 2: The growth efficiency f plotted as a function of the collision velocity u_{coll} for various sizes and size-ratios of colliding aggregates.

The numerical results are shown in Fig. 2, in which growth efficiency f is plotted as a function of collision velocity u_{coll} for various sizes and size-ratios of colliding aggregates. Although we cannot see any size dependence on f, there is a trend that the larger size-ratio makes f larger. This is what we expected as the effect of collisions between different-sized aggregates. However, we do not clearly see an increase in the critical velocity, which is the velocity corresponding to f = 0 and determines the collisional outcomes to be mass gain or mass loss. The critical collision velocity seems to increase a little bit compared to the equal-sized collision case, but its trend is unclear and limited at most 100 m/s.

Discussion and summary: We found that aggregate collisions with large size-ratios N_{target}/N_{proj} lead to large growth efficiency f. This is because offset collisions with large size-ratios closely resemble head-on collisions. Our previous paper showed that aggregates are able to stick with each other at head-on collisions more effectively than at offset collisions [2]. In fact, f is large even at relatively large impact parameter b for the collisions with large size-ratios, compared to equal-sized collisions (Fig. 3). This effect encourages dust growth and planetesimal formation.

On the other hand, the critical collision velocity for dust growth is unchanged even for collisions with a large N_{target}/N_{proj} = 64 (the critical velocity for ice aggregates is less than 100 m/s). This is probably because only the projectile size determines the growth efficiency when the target size is sufficiently large. This is suggested by the fact that the impact energy is not distributed over a wide region within targets (Fig. 1). The collision outcomes would be similar to cratering when the target size is sufficiently large. Given that the critical velocity for silicate aggregates is one order of magnitude less than that for ice [2], silicate aggregates cannot grow through collisions at more than 10 m/s. This suggests that silicate dust is still difficult to grow in protoplanetary disks, in which the collision velocity becomes up to several tens of m/s. We need to consider another mechanism to form silicate planetesimals.

References: [1] Weidenschilling, S. J., & Cuzzi, J. N. (1993), in Protostars and Planets III, 1031. [2] Wada, K., Tanaka, H., Suyama, T., Kimura, H., & Yamamoto, T. (2009), Astrophys. J. 702, 1490. [3] Dominik, C., & Tielens, A. G. G. M. (1997), Astrophys. J. 480, 647. [4] Wada, K., Tanaka, H., Suyama, T., Kimura, H., & Yamamoto, T. (2007), Astrophys. J. 661, 320.

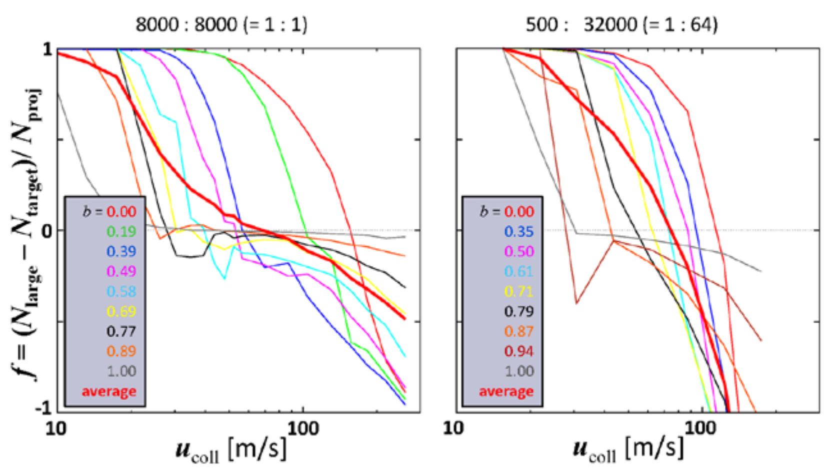

Figure 3: The growth efficiency f as a function u_{coll} for each impact parameter b and their average value. Left: equal-sized collision case. Right: different-sized collision case (size ratio 64).