DENSITY EVOLUTION OF DUST AGGREGATES GROWING IN PROTOPLANETARY DISKS. Toru Suyama, Koji Wada, Hidekazu Tanaka, *Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819, JAPAN, storu@neko.lowtem.hokudai.ac.jp, wada@neko.lowtem.hokudai.ac.jp, hide@lowtem.hokudai.ac.jp.*

Introduction: Planetesimals are formed from dust aggregates in protoplanetary disks. Dust aggregates grow through mutual collisions, gradually settle to the midplane of a disk and form a dense dust layer at the midplane [1-2]. Then planetesimals would be formed in the dust layer through gravitational instability [3-5] or simple coalescence [6-8]. Even if the gravitational instability occurs, dust aggregates should become large aggregates through mutual collision. Thus, collisional growth is important process for planetesimal formation. Small dust aggregate have the fluffy structure. However, dust aggregates are compressed as they grow. Thus, large dust aggregates can not keep such fluffy aggregates. Such compression changes the cross section of dust aggregates and the gas drag force which governs the dust motion. Thus, compression process is important on dust growth. However, most of the previous studies on dust growth in disks assumed compact aggregates and did not consider the evolution of the internal structure of aggregates.

Dominik & Tielens [9] performed a 2D numerical simulation of aggregate collisions. They modelled particle interactions in detail and calculated the motion of each particles directly in their simulation. As a result, they derived a simple recipe for outcomes of aggregate collisions, i.e., compression and disruption. Wada et al. [10] performed 3D simulations of head-on collisions of BCCA clusters. They introduced the pressure and explained the structure evolution in their numerical results. In previous studies on aggregate collision, they consider one collision only. However, aggregates grow through sequential collisions in protoplanetary disks. Thus, it is need to examine structure evolution through not only one collision but also sequential collisions.

In this study, we perform the 3-D simulations of sequential collisions. Our initial aggregates is the resultant aggregate which is obtained by the previous collision. We repeat the calculation of such collision to examine the compression process during aggregate growth. We apply the model described in Wada et al. [10] to our numerical results and we construct the model of the density evolution of dust aggregates growing. As our results, impact compression results in extremely fluffy aggregates.

Numerical procedure: By repeating calculation of an aggregate collision, we describe the growth of aggregates. We perform 3D N-body calculation of aggregate collisions in the same way as Wada et al. [10]. Here, we briefly summarize numerical procedure of N-body calculation. Aggregates consist of a number of spherical icy particles with the radius of 0.1μm. We calculate the motion of individual particles, by integrating the equation of motion for each particle. Each particle is considered as an elastic sphere with the surface energy. Aggregates consist of icy particles. Our particle interaction model is same as Wada et al. [10].

Aggregates are compressed mainly through inelastic rolling motion [9-11]. The (inelastic) rolling energy, $E_{\rm roll}$, is that required for the rolling with a distance, $(\pi/2)r_1$, where r_1 is the radius of the particle. In Wada et al [10], the rolling energy is given by

$$E_{\rm roll} = 6\pi^2\gamma r_1 \xi_{\rm crit}, \quad (1)$$

where γ is the surface energy and $\xi_{\rm crit}$ is the critical displacement for rolling. For icy aggregates with $\xi_{\rm crit} = 8$ Å, $E_{\rm roll}$ is equal to 4.7×10^{-16} J. To compress an aggregate, we need the energy $E_{\rm roll}$, at least.

To examine structure evolution of growing aggregates, we perform simulation of sequential collisions. As an initial condition of collisions, we prepare two identical aggregates with different orientations, as done by Wada et al. [10,11]. In our simulation of sequential collisions, as the initial aggregates, we use the resultant aggregate obtained in the previous collision of simulation while Wada et al. [10,11] used BCCA clusters. Since we consider only collisions with relatively low impact velocities (<5 m/s), fragmentation does not occur in all collisional calculations. Thus, the aggregate mass is doubled at each collision. The simulation starts from a collision of aggregates composed of two particles (i.e., dimers) and ends up with a collision of those composed of 8192 particles (see Fig. 1). We consider only head-on collisions. The oblique collisions would create less compressed aggregates than the head-on collisions. Thus the bulk density of the aggregate obtained in this study is considered to be an upper-limit.

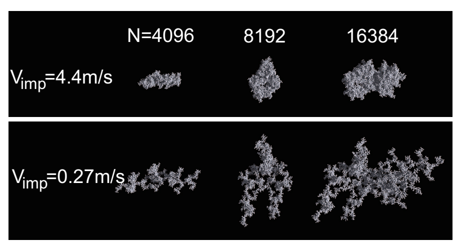

Figure 1: Resultant aggregates obtained from the simulation of sequence collisions with $v_{\rm imp} = 4.4$ m/s (top),and $v_{\rm imp} = 0.27$ m/s (bottom). Aggregates obtained from the high velocity case is more compact than those obtained from the low velocity case.

The initial orientation of the aggregates are randomly chosen at each collision. Since the structure of the resultant aggregate at the collisional simulation depends on the initial orientation, we perform 30 runs for different sets of the initial orientations and take an average of each run.

Results: To examine the compression process quantitatively, we evaluate the (bulk) density of the resultant aggregates. Figure 2 shows density evolution of growing aggregates in those simulations. In all simulations of sequential collisions with constant impact velocities, the aggregate density decreases with their growth.

It is worthwhile comparing the densities of the resultant aggregates with those of BCCA (ballistic cluster-cluster aggregation). At collisions of equal-mass aggregates with sufficiently low velocities, they just stick without compression. Such aggregation is called BCCA. They have very fluffy structure. In Figure 2, dashed lines represent the density of BCCA clusters. For small aggregates created in our simulation, their density changed almost along the curve of BCCA clusters. When the particle number is larger than a critical value, the density is larger than that of BCCA clusters. This is due to compression at collisions. The beginning of compression can be estimated with the equation $E_{\rm imp} \sim E_{\rm roll}$ [9-12]. The critical particle number for compression is obtained as

$$N_{\rm crit} = b\frac{8E_{\rm roll}}{m_1 v_{\rm imp}^2}, \qquad (2)$$

where b is the coefficient of the order of unity and m_1 is the mass of monomers. In Figure 2, we also plot the critical number $N_{\rm crit}$ with points on each density curve, by setting $b = 0.5$. The equation (2) with this value of b reproduces well the beginning of compression in the numerical results. After the beginning of compression, the aggregate density keeps on decreasing.

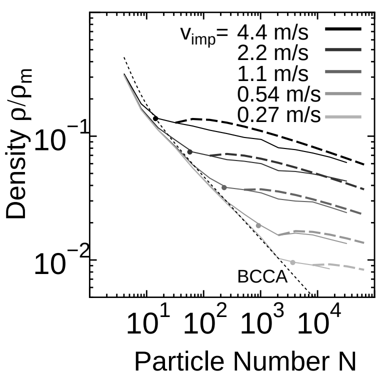

Figure 2: The solid lines show the numerical results, the dotted line shows the density of BCCA clusters and the dashed lines show the model of the equation (5). The points indicate the critical particle number $N_{\rm crit}$ for aggregate compression. The curve by the equation (5) is started from $N \simeq 2N_{\rm crit}$.

Model of density evolution: Wada et al. [10] examined the compression process through the 3D numerical simulation of collisions between BCCA clusters. They obtained an "equation of state" of aggregates and succeeded in reproducing the aggregate compression in numerical simulations with the equation of state. As an increase in the impact energy $E_{\rm imp}$, the resultant aggregate is more compressed and its volume V decreases. Between the changes $dE_{\rm imp}$ and dV, the following relation is satisfied:

$$dE_{\rm imp} = -PdV, \qquad (3)$$

where the positive coefficient P is the pressure. From their numerical results, Wada et al. [10] obtained the formula of the pressure as

$$P = 6.4\frac{E_{\rm roll}\rho_m}{m_1}\left(\frac{\rho}{\rho_m}\right)^{13/3} N^{2/3}. \qquad (4)$$

Integrating the equation (3) with (4), we obtain the volume of the resultant aggregate as a function of $E_{\rm imp}$, which reproduces the numerical results by Wada et al [10] with high accuracy.

The density change by impact would be expressed by the integration of the equation (3) in the model by Wada et al.;

$$\frac{d\ln\rho}{d\ln M} = -\frac{1}{5} + \frac{1}{0.5\ln 2}\left(\frac{M}{m_1}\right)^{-2/3}\left(\frac{\rho}{\rho_m}\right)^{-10/3}\frac{E_{\rm imp}}{NE_{\rm roll}}, \qquad (5)$$

where M ($\equiv m_1 N$) is the mass of the aggregate and ρ_m is the density of particles. This equation describes the density evolution of growing aggregates. The second term in the RHS represents compression of aggregates through rolling. On the other hand, the first term of the RHS reduces the aggregate density. Because of this first term, the aggregate density decreases even for collisions $E_{\rm imp} \gg E_{\rm roll}$, as seen in Figure 2.

Evolution of dust density in protoplanerary disks: We discuss about the evolution of the density of dust aggregates in protoplanetary disks. When dust aggregates move against the disk gas, they receive the gas drag force and the gravitational force from the central star. The gas drag force governs the dust motion. The impact velocity of dust aggregates depends on the ratio of the mass to the cross section. Substituting the impact velocity in disks into the equation (5), we obtain the density evolution in disks. Using typical disk model [13], the maximum velocity of dust aggregates in protoplanetary disks is given by 50 m/s. At the collision of $v_{\rm imp} \simeq 50\,{\rm m/s}$, the density of the resultant aggregate is $\simeq 10^{-4}\ {\rm g/cm^3}$ from the equation (5). As the impact velocity increases, the density increases. Thus, at the collision of the maximum impact velocity, the resultant aggregate have the maximum density. The maximum density of dust aggregates is extremely low ($\sim 10^{-4}\ {\rm g/cm^3}$). It means that the impact compression results in extremely fluffy aggregates.

Reference: [1]Safronov, V. S. 1969, Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets (NASA Tech. Trans. F-677) (Nauka: Moscow). [2]Nakagawa, Y., Nakazawa, K., & Hayashi, C. 1981, Icarus, 45, 517 [3]Goldreich, P., & Ward, W. R. 1973, ApJ, 183, 1051 [4]Youdin, A. N., & Shu, F. H. 2002, ApJ, 580, 494 [5]Johansen, A.*et al.* 2007, Nature 448 [6]Weidenschilling, S. J., & Cuzzi, J. N. 1993, In Protostars and Planets III (E. H. Levy and J. I. Lunine, Eds.), pp. 1031. Univ. of Arizona Press, Tucson. [7]Stepinski, T. F., & Valageas, P. 1997, [8]Brauer, F.*et al.* 2007, A&A 469 1169 [9]Dominik, C., & Tielens, A., 1997, ApJ, 480, 647 [10]Wada, K.*et al.* 2008, (submitted) ApJ [11]Wada, K.*et al.* 2007, ApJ, 661, 320 [12]Blum, J. 2004, in ASP Conf. Ser. 309, Astrophysics of Dust, ed. A. N. Witt, G. C. Clayton, & B. T. Draine (San Francisco: ASP), 369 [13]Adachi, I., Hayashi, C., & Nakazawa, K. 1976, Prog. Theor. Phys., 56, 1756