PLANETESIMAL FORMATION THROUGH GRAVITATIONAL INSTABILITY. I. Furuya, Y. Nakagawa, *Faculty of Sciences, Kobe University, Kobe 657-8501, Japan (furup@kobe-u.ac.jp)*, H. Daisaka, *Department of Astronomy, University of Tokyo, Tokyo 152-8551, Japan*.

Introduction. Two prevailing processes of planetesimal formation are proposed. The first is the gravitational instability of a dust layer (e.g., Safronov 1969, Hayashi 1972, Goldreich and Ward 1973). The second is the growth through the mutual sticking of dust particles in a turbulent nebula (Weidenschilling and Cuzzi 1993, Stepinski and Valageas 1997). We consider the first one in this study.

The solar nebula is considered to be turbulent more or less at early stages. After such turbulent motion has decayed, dust particles settle toward the central plane of the nebula (Weidenschilling 1980, Nakagawa $et\ al.$ 1981, 1986). The linear stability analysis gives the condition for gravitational instability of a self-gravitating disk in terms of Toomre's Q-value as

$$Q \equiv \frac{\sigma \Omega_{\rm K}}{\pi G \Sigma} < 1, \qquad (1)$$

where σ is the radial velocity dispersion, $\Omega_{\rm K}$ is the Keplerian angular velocity, and Σ is the surface density of the layer. When the dust settling progresses and the above condition is met, the dust layer is unstable against axisymmetric perturbations of wavelengths around the critical wavelength

$$\lambda_{\rm crit} = \frac{2\pi^2 G \Sigma}{{\Omega_{\rm K}}^2}, \qquad (2)$$

and breaks into rings with the radial width $\simeq \lambda_{\rm crit}$. The mass of a planetesimal is estimated as

$$m_{\rm theor} = \pi \Sigma \left(\frac{\lambda_{\rm crit}}{2} \right)^2, \qquad (3)$$

by assuming that rings break into many pieces with the azimuthal wavelength similar to $\lambda_{\rm crit}$. In this study, we reproduce the gravitational fragmentation of a particulate disk by 3D local N-body numerical simulations in order to examine the process of planetesimal formation and to estimate the mass of a planetesimal.

Method. We follow the 3D motions of particles in a square $L \times L$, where the L is the size of the square in the x or y direction, using the rotating Cartesian coordinates, called the Hill coordinates (Wisdom and Tremaine 1988, Salo 1995, Daisaka and Ida 1999). We then apply periodic shearing boundary conditions. In our study, we take only the mutual gravitational forces and inelastic collisions between particles into account, and we neglect the disruption, sticking of the particles and drag by nebular gas. We calculate the mutual gravitational forces between particles by the GRAPE systems, which are the special-purpose computer for calculation of gravitational forces (e.g., Sugimoto $et\ al.$ 1990). A collision is detected when two or more particles approach and overlap each other. We adopt a smooth inelastic hard sphere collision model. The relative velocity after a collision is given by

$$v_{\rm n}' = -\epsilon v_{\rm n}, v_{\rm t}' = v_{\rm t}, \qquad (4)$$

where $v_{\rm n}$, $v_{\rm n}'$ and $v_{\rm t}$, $v_{\rm t}'$ are the normal and tangential components of the relative velocities before and after the collision, respectively, and ϵ is the restitution coefficient in the normal direction. In all our simulations, we set $\epsilon = 0.01$.

Results. We perform the simulation of $N = 11650$ particles in the case of the radial distance around 0.02AU, the surface density of the dust layer $\Sigma = 2.67 {\rm g\,cm^{-2}}$, the material density of particles $\rho = 2\,{\rm g\,cm^{-3}}$, and the particle radius $r_0 = 10\,{\rm cm}$. The size of the calculation square $L = 10\lambda_{\rm crit}$ (= 61m). We use the initial conditions that the particle spatial distribution is uniform (Fig.1(a)) and the velocity dispersion of particles is large enough for the layer to be stable ($Q > 1$).

We find that planetesimals are formed through three stages (see Fig.1). The layer becomes gradually thinner and unstable with energy dissipation due to the inelastic collisions between particles. In this stage, non-axisymmetric wake-like structures appear (Fig.1(b), stage 1). The first-generation clumps are formed in these denser wakes (Fig.1(c), stage 2). At last, the first-generation clumps grow to two large clumps through mutual fast coalescence (Fig.1(d), stage 3). Rings assumed in the linear perturbation theory do not appear.

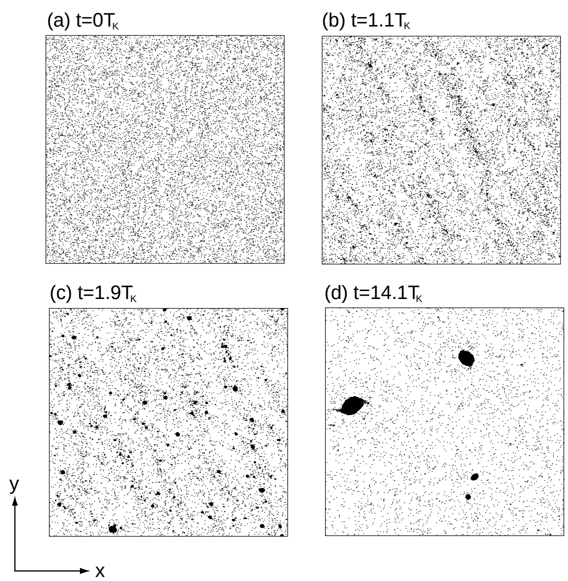

Figure 1: Snapshots of particle distribution on the x-y plane at $t = 0,\ 1.1,\ 1.9,$ and $14.1 T_{\rm K}$, where the $T_{\rm K}$ is the Keplerian period. Figures (a) to (d) illustrate (a) initial distribution, (b) non-axisymmetric wake-like structure, (c) first-generation clumps, and (d) second-generation clumps, respectively.

The Q-value of the simulated system decreases due to inelastic collisions at the beginning (Fig.2(a)). When Q reaches nearly 2, the first-generation clumps are formed. Once the clumps are formed, the Q-value begin to increase with the

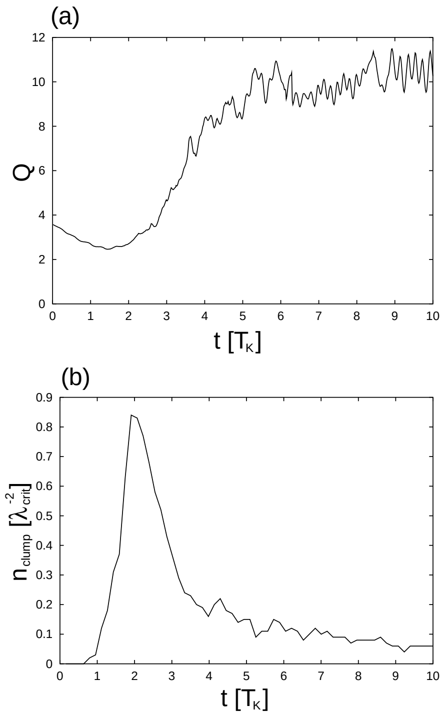

Figure 2: (a) The time evolution of Q-value and (b) the time evolution of the number of clumps in the area ${\lambda_{\rm crit}}^2$, respectively.

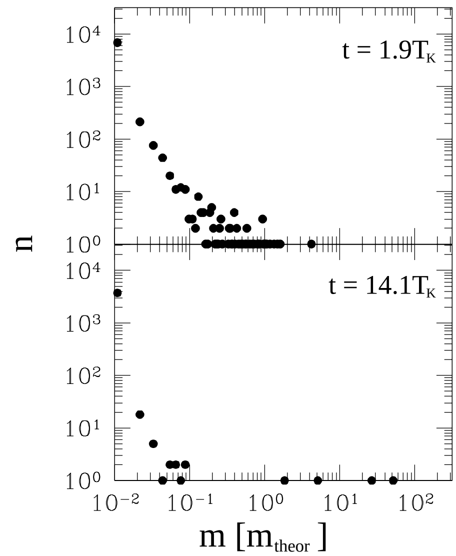

Figure 3: The mass distribution of clumps at $t = 1.9$ (first-generation clumps) and $14.1 T_{\rm K}$ (finally formed two large clumps), respectively.

growth of clumps and keeps nearly constant after $t \simeq 8T_{\rm K}$, where $T_{\rm K}$ is the Keplerian period. Figure 2(b) shows that the number of clumps increases until about $2T_{\rm K}$ (because new clumps are formed one after another) and decreases afterward (because first-generation clumps coalesce one another). Here, we define a clump with the condition that the constituent particles are gravitationally bound, using the following procedures. At first, we detect an aggregate of particles whose mutual distances are smaller than $2 \times 2r_0$. Next, we remove particles having relative velocity larger than the escape velocities of the aggregate. At last, if the aggregate still keeps more than ten particles, we regard it as a clump.

The first-generation clumps have the mass range of about 0.1-4$m_{\rm theor}$ and do not have a characteristic mass (at $t = 1.9T_{\rm K}$ in Fig.3). The masses of the largest and second-largest clumps which are formed finally are about 50 and $30\, m_{\rm theor}$, respectively (at $t = 14.1T_{\rm K}$ in Fig.3).

Conclusions. At first, we have showed that the planetesimals are formed through three stages: (1) appearance of non-axisymmetric wake-like structure, (2) formation of first-generation clumps, and (3) growth of first-generation clumps through mutual fast coalescence. No ring assumed in the linear perturbation theory appears in these process. Next, we have showed that the masses of the first-generation clumps have the range of 0.1-4m_{theor} (not have a characteristic mass) and the clumps finally formed by mutual fast coalescence is about $50\, m_{\rm theor}$, respectively.

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