

# Numerical simulations on the collision, adhesion, and growth of dust particles in turbulent gas in a protoplanetary disk

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In a protoplanetary disk, dust grains, which are icy or rocky microscopic particles, are present at about one percent of gas mass. The dust grains collide and adhere with each other to grow in size repeatedly in turbulent gas of a protoplanetary disk. Planetesimals are widely believed to form as a consequence of this hierarchical coagulation from submicron-size dust particles to kilometer-size bodies in a protoplanetary disk. However, it has been argued that there are several physical barriers such as bouncing and radial drift barriers in the planetesimal formation process, and these remain unresolved, especially for silicate dust. In recent years, as a possible solution to these problems, the effect of turbulent clustering of dust grains has been attracting attentions.

In previous studies, it was pointed out that the clustering of particles by turbulence promotes adhesion growth (Pan et al, ApJ2011), and the statistics such as the collision velocity of dust particles in turbulent flow were investigated by a direct numerical simulation (DNS) of turbulence, solving the Navier–Stokes equations (Pan and Padoan, ApJ 2015). Recently, a series of large-scale DNSs of turbulence was conducted to study the velocity distribution of colliding particles in the turbulent flow and the dependence on flow nonlinearity (Reynolds number) (Ishihara et al, ApJ2018). However, numerical simulations on the coagulation process of dust particles were not performed. Therefore, whether dust grains grow hierarchically has not been clarified.

In this study, we developed a parallel code (using MPI and OpenMP) to simulate the collisional adhesion process of dust particles, in which the critical collision velocity (Wada et al, A & A, 2013) is taken into account, and investigated the adhesion processes of  $512^3$  dust particles using a large-scale DNS of turbulence.

As a result, we have found the following by the analyses of the obtained data:

- (1) Dust particles collide with each other within the critical collision velocity preferentially at positions with smaller enstrophy (intensity of vorticity), while dust particles collide with the critical or higher collision velocity at positions with larger enstrophy.
- (2) Even if the average collision speed exceeds the critical collision velocity, the collisions within the critical collision velocity can occur repeatedly, and thus rapidly growing dust grains do exist.
- (3) The sticking probability of dust particles directly obtained by our simulations is larger than that estimated by the previous DNS data analysis (Ishihara et al ApJ 2018).
- (4) The Reynolds number dependence of the dust motion for grains with long stopping time (the response time to flow change) is very weak. Hence, even in protoplanetary disk turbulence with much larger Reynolds number, the same growth process as in this study is expected.

The reasons and implication of the above results will be discussed by conducting the additional data analysis.

Keywords: Protoplanetary disk, Planetesimal formation, Numerical simulations on the collision, adhesion, and growth of dust particles

