Multi-scale turbulent flow structures and particle collision statistics on planetesimal formation

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According to the standard model of planet formation, planetesimals are believed to be formed by repeated collisions and coalescence of dust particles that exist in a protoplanetary disk. However, fragmentation and bouncing barriers are still obstacles to collisional growth, especially for silicate dust. Since the dust particles are carried by turbulent gas, it is important to understand the role of turbulence in planetesimal formation. In order to accurately represent turbulence, several studies on planetesimal formation based on direct numerical simulations (DNSs) have been performed in recent years. Pan & Padoan (2013, 2014, 2015) and Pan et al. (2014) performed a DNS of weakly compressible turbulence (Re˜1,000, where Re is Reynolds number) laden with inertial particles and showed that the rms relative velocity of particle pairs obtained by DNS is smaller than that by turbulent model developed by Ormel & Cuzzi (2007). Ishihara et al. (2018) conducted DNSs of incompressible turbulence at high Re (up to Re˜16,100) to study the particle clustering and showed that the collision statistics of particles with large inertia are not so sensitive to the Re. However, the barriers mentioned above are still remain unsolved.

Recently, Picardo et al. (2019) quantified the correlation between particle collisions and flow structures in turbulence and showed that the collision velocities of particles with small inertia in vortical regions are smaller than those in straining regions. Their result indicates that the collision speed of the particles depends on the turbulence structures. Sakurai et al. (2019) extracted the multi-scale vorticity structures by using a coarse-graining method and showed the distribution and motion of inertial particles around the high-vorticity regions depends on the coarse-grained level and on the particle inertia. These results motivated us to study the relationships between inertial particle statistics and coarse-grained turbulent structures.

In this paper, we use the datasets obtained by Ishihara et al. (2018) (Re˜16,100) and investigate the particle collision statistics in multi-scale turbulent structures. The particle inertia is characterized by Stokes number St, which is the ratio of particle stopping time to the large-eddy time scale in turbulence, and the values are from 0 to 0.234. To extract the multi-scale turbulent structures, we use the second invariant of the velocity gradient tensor calculated from the velocity field coarse-grained with a low-pass filter. The positive and negative values of the second invariant represent the vortical and straining regions, respectively, in each coarse-grained level. The cut off wavenumber kc for the low-pass filter are set as kc/kmax = (1/2)^n (n=0,1,⋯6), where kmax is the maximum wavenumber in the DNS. We use the critical collision velocity obtained by Wada et al. (2013) to evaluate the sticking rates of colliding particles. Our results are as follows:

(1) The coarse-grained second invariant PDF at particle position depends on kc and St.

(2) The average relative velocity of particle pairs in the vortical regions can be 70-80% compared to that in the straining regions.

(3) As the coarse-grained level increases, the particles' inertia with the largest difference of relative velocity between in vortical and straining regions increases.

(4) In the case of $k_c/k_{max} = 1/64$ and St = 0.234, the sticking rates of colliding silicate dust (at 1AU from the central star) and icy dust (at 5AU) in the vortical regions are 3.14% and 88.4%, respectively. These values are 1.31 and 1.09 times higher than the corresponding values in the whole regions.

Our results show that the particles with large inertia in the coarse-grained vortical regions are more likely to grow without fragmentation or bouncing because the collision speeds in the regions are slightly lower than those in the other regions.

Keywords: planetesimal formation, turbulence, inertial particle