Effect of the compressibility of turbulent flows on dust particle collision statistics in a protoplanetary disk

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Planetesimals are believed to form by hierarchical coagulation from submicron-size dust particles to kilometer-size bodies in turbulent flows in a protoplanetary disk. However, several barriers, e.g., radial drift, bouncing, and fragmentation barriers, in the planetesimal formation process are not completely resolved, especially for silicate dust. To resolve these barriers, it is important to accurately understand the role of turbulence in the coagulation process.

In the Minimum-mass Solar Nebula (MMSN) Model (Hayashi 1981), the Reynolds number (Re) and the Mach number (Ma) of turbulence in protoplanetary disks range Re=10^8~10^11 and Ma=0.01~0.32, respectively. Pan et al. (2011) conducted an approximate simulation of compressible turbulence (Ma~1.0) and showed that turbulent clustering may considerably enhance the particle collision rate. Pan & Padoan (2013, 2014, 2015) and Pan et al.(2014) peformed a direct numerical simulation (DNS) of the Navier–Stokes equations on weakly compressible turbulence (Re~1000 and Ma~0.1) at low Re to study the effect of turbulent clustering. Pan & Padoan (2015) found that the rms relative velocity of particle pairs is smaller by more than a factor of two compared to that by turbulent model (Ormel & Cuzzi 2007). Their studies demonstrated that the turbulent clustering should be taken into account to consider the coagulation process.

Recently, Ishihara et al (2018) performed DNSs of incompressible turbulence at high Re (up to Re=16100) to study the motion of dust particles in turbulence. They showed that the collision statistics of the dust particles with large inertia are not so sensitive to the Reynolds number and confirmed that they are consistent with those by Pan & Padoan or Pan et al at low Re. However, the effect of compressibility of turbulence on the collision statistics is not yet quantitatively investigated.

In this paper, we perform DNSs of incompressible and compressible turbulence with Ma=0.1 and 0.3 and set the ratio of dilatation component (ed) and solenoid component (es) of the mean energy dissipation rate (ed/es) to 0.01 and 0.1 to study quantitatively the effect of compressibility of the inertial particle collision statistics. The motion of inertial particles is characterized by the Stokes number (St=tp/T, where tp is the particle stopping time and T is the time-scale of largest eddies), and we track eight sets of inertial particles with from St=0 to St=0.3. Our results are as follows:

(1) The compressibility of turbulent flow is characterized by both of Ma and ed/es.

(2) In case of Ma=0.3, the local Ma can exceed unity so that shocklets can be generated in the turbulent flow.

(3) The local Mach number is high at positions with higher enstrophy.

(4) In case of Ma=0.1-0.3, relative velocity of colliding particles and collision kernel have weak Mach number dependence but may depend when the value of the ratio of ed/es is large.

Our results show that compressibility considered in protoplanetary disk turbulence has little influence on particle collision statistics.

Keywords: planetesimal formation, turbulence, inertial particle

