Effect of compressibility of turbulence in the coagulation process of the dust particles in the protoplanetary disks

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Planetesimals are thought to be the precursors of both Earth-like planets and the cores of gas giants and ice giants. The coagulation of dust particles is a key process in planetesimal formation. It is widely believed that the planetesimals form as a consequence of the hierarchical coagulation from submicron-size dust particles to kilometer-size bodies in protoplanetary disks. However, the radial drift and bouncing barriers in planetesimal formation 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 characteristic velocity U of turbulence in the protoplanetary disk are given as functions of the radial distance R from the central star and the turbulence parameter a. The typical value of α is 10^{-4}~10^{-1} (Cuzzi et al. 2001) and correspondingly Re=10^{8}~10^{11} and U=11m/s~350m/s at R=1au. On the other hand, Wada et al. (2013) estimated the critical collision velocity u_c below which fluffy dust aggregates can coalesce: u_c=60~80 m/s for ice dust and u_c=6~8 m/s for silicate dust. According to the Ormel & Cuzzi (2007), the rms relative velocity of the dust particles is an increasing function of the inertia (size) of the particles and, for the particles with large inertia, it exceeds u_c .

Pan et al (2011) used an approximate simulation of compressible turbulence and showed that the turbulence may promote the coagulation process of the dust particles. Pan & Padoan(2013, 2014, 2015) and Pan et al.(2014) used a direct numerical simulation (DNS) of weakly compressible turbulence 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 as compared to that by Ormel & Cuzzi. Their studies showed 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, and confirmed that the results are almost consistent with those by Pan & Padoan or Pan et al at low Re. The results showed that the collision statistics of the dust particles with large inertia are not so sensitive to the Reynolds number. But it was assumed that the collision statistics are not so sensitive to the compressibility of turbulence. According to the MMSN model, the Mach number Ma of turbulence in protoplanetary disks ranges 0.01~0.32 for $\alpha=10^{-4}$~10^{-1}. Therefore the turbulence is regarded as subsonic and thus essentially incompressible. However, the effect of compressibility of turbulence on the collision statistics has not been investigated yet quantitatively.

In this paper, we perform DNSs of compressible turbulence with Ma=0.1~0.5, track the motion of inertial particles (Stokes number 0~0.3) in the turbulent flow field and study quantitatively Ma-dependence of the collision statistics. Also, we perform DNSs of incompressible turbulence and compare the results with those by compressible turbulence. Our results are as follows: (1) The enstrophy decreases with Ma. (2) When Ma<0.3, the local Ma is less than 1 so that there are no shocklets in the turbulence fields. (3) Weak Ma dependence is observed in the radial distribution functions. (4) The rms relative velocities of particles with small inertia in the compressible turbulence at Ma larger than 0.4 are slightly larger than those obtained in the compressible turbulence at Ma ~ 0.1 (or in incompressible turbulence).

Our results showed that the collision statistics of the dust particles with large inertia are insensitive to the values of Ma (0~0.5) and also that compressibility of turbulence may play a role in the collision statistics of the dust particles with small inertia.

Keywords: planetesimal formation, turbulence, inertial particle