The influence of dust evolution on the vertical shear instability in protoplanetary disks

*Yuya Fukuhara[1], Satoshi Okuzumi[1]

1. Department of Earth and Planetary Sciences, Tokyo Institute of Technology

Protoplanetary disks are places of planet formation. Gaps in disks revealed by recent high-resolution radio observations (e.g., Andrews et al. 2018) may indicate that planets form far away from the central stars (10–100 au). How dust in such distant regions grows into planetesimals and planets remains an open question.
To address this question, it is crucial to understand turbulence in the outer regions of protoplanetary disks. Turbulence in protoplanetary disks is known to induce collisional fragmentation and diffusion of dust particles (e.g., Ormel & Cuzzi 2007), both of which prevent planetesimal formation. Turbulence can also promote planetesimal formation by selectively collecting particles of a particular size (e.g., Pan et al. 2011). However, it is still unclear what mechanism mainly drives turbulence in outer disk regions.
In this study, we discuss the viability of the vertical shear instability (VSI) as a mechanism driving turbulence in outer disk regions. The VSI is a hydrodynamic instability of accretion disks with a vertical gradient in the rotation velocity and operates when the thermal relaxation time of the disk gas is much shorter than the orbital period. Previous studies (Pfeil & Klahr 2019) suggest that the VSI is apt to occur in outer disk regions. However, the calculation of the thermal relaxation time in the previous studies assumed micron-sized dust grains, which is inapplicable to circumstances where dust evolution has already proceeded.
The purpose of this study is to clarify the influences of dust evolution on the spatial extent of the VSI-unstable region. To this end, we use a model based on the local stability analysis of the VSI (Malygin et al. 2017; Pfeil & Klahr 2019) and study how the VSI-unstable region changes with the maximum size and total amount of dust particles. The vertical distribution of the particles is determined from the balance between sedimentation and turbulent diffusion, assuming a given strength of VSI-driven turbulence.
We find that the VSI-unstable region shrinks as the maximum particle size increases, and/or the total amount of dust decreases. This is because thermal relaxation becomes faster as small dust grains are removed. In the particular case where the total disk mass is 1% of the solar mass, the VSI-unstable region is confined within one gas scale height above and below the midplane if the maximum particle size is larger than 1 mm, or the dust-to-gas surface density ratio is below 0.1% .
Our results suggest that dust evolution suppresses VSI-driven turbulence. Given that turbulence generally prevents dust coagulation, the coevolution of dust and VSI may promote further dust growth. Our results also imply the presence of positive feedback between dust setting and VSI suppression, namely, dust settling makes VSI weaker and thereby further promotes the settling itself.

Keywords: Protoplanetary disk, vertical shear instability