Abstract

The temperature and opacity structure of planet forming accretion disks (PFDs), which is shown by the local dust content in the disk, is directly influenced by the underlying turbulence present within. The dynamic activity generating this turbulence (arising from several recently identified mechanisms), in turn, is determined by the local thermodynamics which is largely set by the local abundance of dust so that the two processes are intimately linked [3-13]. In this talk we present the results of a study in which the temperature-opacity fields arising from global turbulent disk evolution models [14-15] are used to assess which of the currently considered linear instability mechanisms are operating in driving hydrodynamic turbulence in stably stratified PFDs. Some preliminary results include (i) currently published global disk models with parametrized turbulent intensities appear to give rise to opacities that are self-consistent with the small-scale linear instabilities driving turbulence, (ii) the vertical shear instability [5-8] and the convective overstability [12-13] appears to operate robustly in the 1-100 AU range in both early and mid stages of young disks, while the zombie vortex instability [9-11] generally occurs in the outer parts of the disk (>50-100 AU) and becomes prominent during evolved epochs of PFDs.

Hydrodynamic Turbulence in Planet Forming Disks

Bulk interiors of disks where planetesimals form are non-magnetized. Listed below are various instability mechanisms identified to drive down-cascading turbulence. Note that the turbulent Reynolds number $Re_{turb}$ relates to the "$\alpha$" parameter via $\alpha = 1 / Re_{turb}$.

**Vertical Shear Instability (VSI) [5-8]**

- **Instruments:** Disk radial shear dependence results in vertical (baroclinic shear) but also vertically stably stratified against convection.
- **Short cooling times - $\tau_c < 1$**; $\alpha < 1$ cm$^{-1}$.
- **Mechanism:** Linear. Angular momentum exchange b/w radial-vertically adjacent fluid elements results in lower final energy state.
- **Quality:** Vertical shear instability.
- **Secondaries:** Linear mode.
- **Turbulent response:** $\alpha = 10^{-1} - 10^{-2}$

**Zombie Vortex Instability (ZVI) [9-11]**

- **Instruments:** Flow profiles deviating from Keplerian (~ jet-like). 3D disturbances. Long cooling times; $\tau_c > 1$, $\alpha > 50$ cm$^{-1}$.
- **Mechanism:** Linear. Resonance between Doppler shifted Rossby wave frequency and buoyancy oscillation at critical layer.
- **Quality:** Nonlinear generation of jet flows at critical layers. Spreading/Outcome.
- **Secondary:** ZVI (self-replicating jets/vortices) and non-axisymmetric Rossby wave inst.
- **Turbulent response:** $\alpha \leq 10^{-1}$

**Convective Overstability (COV) [12-14]**

- **Instruments:** Keplerian flow with radial entropy gradient. 3D disturbances.
- **Mechanism:** Buoyant instability affected by episodic oscillations.
- **Quality:** Vertical vorticity rolls. Complex flow structure.
- **Secondary:** Elliptic instability but vortex not destroyed.
- **Turbulent response:** $\alpha = 10^{-1} - 10^{-2}$

**Opaques Arising from Hydrodynamic Disk Turbulence**

The presence of turbulence depends upon the main opacity sources in the disk itself, which, in turn, depend upon the type, size and distribution of grains. The distribution and growth of grains depends back upon the underlying turbulence in disk – e.g., consider that turbulent velocities induce vertical size-dependent lofting of dust which prevents midplane settling and subsequent drainage into the star. We examine the results of 3-D turbulent disk models that have detailed modeling of growth and drift of dust particles. Given their distributions, we re-calculate these "turbulent" opacities as a function of disk position and ask the next logical question: are the disk turbulence mechanisms and subsequently arising turbulent opacities SELF-CONSISTENT?

Dust accumulation: Viable primary parent bodies of terrestrial planetesimals grew to 100 km sizes before heating and collisional disruption [4]. Growth to these scales via sticking physics involves overcoming various barriers in the mm-10's km range (bouncing, collisional disruption, drift, gravitational). Effectiveness of each mechanism involves clarifying turbulent state of gaseous cold disks. Turbulent concentration (TC) and streaming instabilities [51] also involved in particle collection – latter stage process. Pebble accretion might be playing a role too [4,16].

PP-disk turbulence: Until recently, non-magnetized portions of thin pp-disks which are the locations where planetesimals are manufactured, thought to be hydrodynamically inactive. 3 promising turbulence mechanisms arising from linear instabilities have been identified that can lead to hydrodynamic turbulence in pp-disks. (Other nonlinear/subcritical transitions also possible including subcritical baroclinic instability [3,17].)

**Primary Mechanisms**

- Vertical Shear Instability
- Zombie Vortex Instability
- Convective Overstability
- Rossby Wave Instability
- Elliptic Instability

**Secondary Mechanisms**

- Downscale Entrainment Cascade
- Zombie Vortex Instability
- Zombie Vortex Instability
- Dragging Instability

Turbulent Response

- $\alpha = 4 \times 10^{-5}$

**Notes and references:**


Acknowledgements: This work was supported in part through the Senior NPP. Thanks to many discussions with our colleagues including Karim Shariff, Oliff Gressel, Vladimír Lyra, Richard Nelson, Hubert Klahr, Phil Marcus, Min-Kai Lin, Eyal Heffetz, Ron Yellin-Bergovoy, Giora Shaviv, Oded Regev, Adi Nussbaumer.

**Figure 1.** Plot showing vorticity field of num. sim. of fully developed VSI.

**Figure 2.** Plot showing time sequence of vertical vorticity field of num. sim. of fully developed ZVI [9].

**Figure 3.** Plot showing time evolution of vertical vorticity field of numerical simulation of fully developed COV [12].

**Figure 4.** Study undertaken to examine detailed growth of particles in simplified 1-D disk models with turbulence modeled using aforementioned alpha-disk modeling. Above snapshot shows state of disk after 200,000 yrs after formation. Mean temperature, surface densities and dominant particle masses (by dominant size) shown as a function of disk radius. These are used as inputs for calculating turbulence mechanisms below.

**Figure 5.** Turbulent Rosseland mean opacities given in units of cm$^2$/g. Degree of turbulence is given by $\alpha = 4 \times 10^{-5}$. This figure derived from results of Fig. 4.