OPACITIES AND TURBULENCE IN COLD PLANET FORMING ACCRETION DISKS

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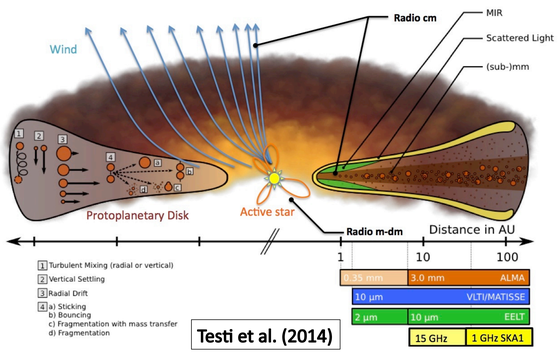
Abstract The temperature and opacity structure of planet forming accretion disks (PFAD), which is shaped by the local dust content in the disk, is directly influenced by the underlying turbulence present within. The dynamic activity generating this turbulence (arising from several recently identified 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 likely to be operational in driving hydrodynamic turbulence in stably stratified PFADs. 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 instabilitles 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 epochs 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 PFADs.

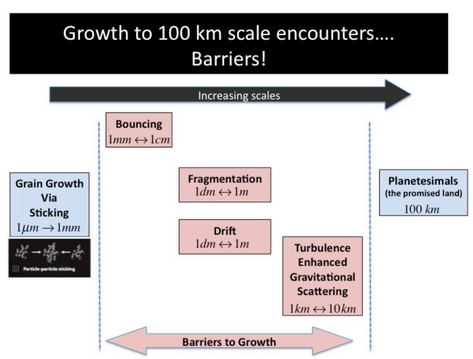
Dust accumulation: Viable primary parent bodies of terrestrial planetesimals grew to 100 km sizes before heating and collisional disruption [4]. Growth to these scales via sticking physics involves overcoming various barriers in the mm-10's km range (bouncing, collisional disruption, drift, gravitational).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

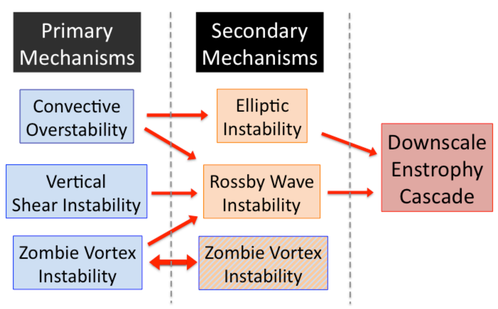
PP-disk turbulence: *Until recently*, **non-magnetized portions** of thin pp-disks which are the locations where planetesimals are manufactured, thought to be hydrodynamically inactive. 3 promising turbulence mechanisms *arising from linear instabilities* have been identified that can lead to hydrodynamic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



Testi et al. (2014)

Chondrules (left)– mm-sized grains of various flavors (e.g. pyroxenes, olivenes and others) **Chondrites** (right)– larger sized bodies that are fragments of asteroids (100 km scales). Show collection of chondrules (of various types).





Hydrodynamic Turbulence in Planet Forming Disks

Bulk interiors of disks where planetesimals form are non-magnetized. Listed blow are various instability mechanisms identified to lead to down-cascading turbulence. Note that the turbulent Reynolds number Re_{turb}, relates to the "α" parameter via: $\alpha \equiv 1/\mathrm{Re}_{turb}$.

Vertical Shear Instability (VSI) [5-8]

Ingredients: Disk radial temperature dependence results in vertical (baroclicnic shear) but also vertically stably stratified against convection. Short cooling times - $\Omega\tau << 1$. opacities $\kappa_r < 1\,\mathrm{cm}^2/\mathrm{gm}$.

Mechanism: Linear. Angular mom. exchange b/w radial-vertically adjacent fluid elements results in lower final energy state. Sloping convection (Earth's weather layer analog)

Quality: Axisymmetric rad. short, nearly incompressible motions.

Secondary Transition: Non-axisymmetric RWI

Turbulent response: $\alpha \sim 10^{-4} - 10^{-3}$

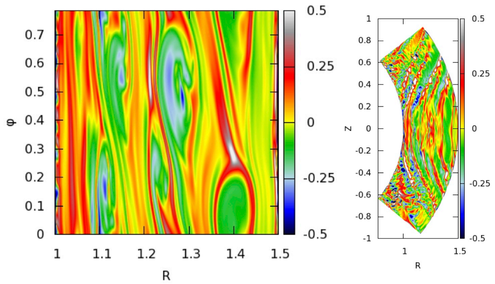


Figure 1. Plot showing vorticity field of num. sim. of fully developed VSI. $H/R = 0.2,\ \Omega\tau = 0.1$ Left image - Disk midplane. Right panel: vertical cut. From ref [8].

Zombie Vortex Instability (ZVI) [9-11]

Ingredients: Flow profiles deviating from Keplerian – jet-like. 3D disturbances. Long cooling times: $\Omega\tau >> 1 \leftrightarrow \kappa_r > 50\,\mathrm{cm}^2/\mathrm{gm}$.

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.

Secondary Transition: ZVI (self-replicating jets/vortices) and non-axisymmetric Rossby Wave Inst. Turbulent downscale enstrophy cascade.

Turbulent response: $\alpha \le 10^{-3}$

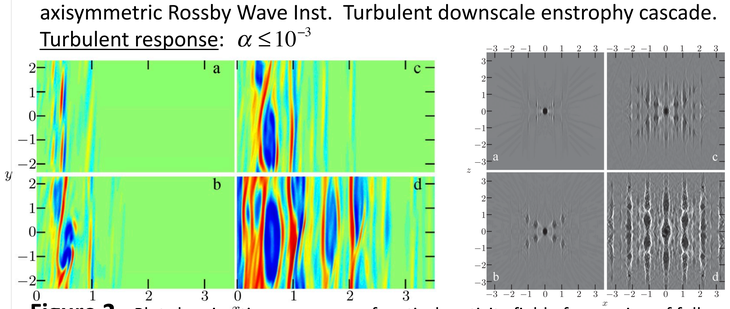


Figure 2. Plot showing time sequence of vertical vorticity field of num. sim. of fully developed ZVI [9]. Left image - Disk midplane (x-rad., y-azi). Right image: vertical cut. The spreading self-replicating quality of the process evident.

Convective Overstability (COV) [12-14]

Ingredients: Keplerian flow with radial entropy gradient. 3D disturbances.

Medium cooling times: $\Omega\tau \sim 1 \leftrightarrow \kappa_r \sim 1 - 50\,\mathrm{cm}^2/\mathrm{gm}$.

Mechanism: Buoyant instability affected by epicyclic oscillations.

Quality: Vertical vorticity rolls. Complex flow structure.

Secondary Transition: Elliptic instability but vortex not destroyed.

Turbulent response: $\alpha \sim 10^{-4} - 10^{-3}$

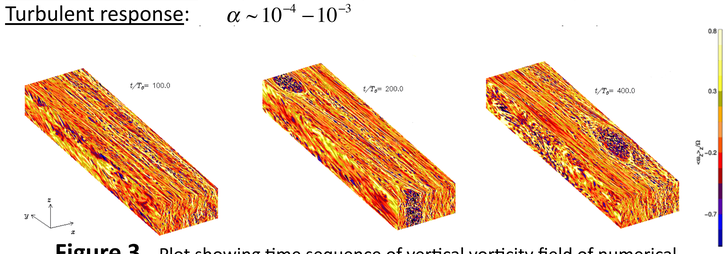


Figure 3. Plot showing time sequence of vertical vorticity field of numerical simulation of fully developed COV [12]. Uniform state develops into vertical vorticity roll which develops small scale structure via elliptical instability. Vortex continually fed by the underlying linear convective overstability.

Opacities Arising from Hydrodynamic Disk Turbulence

The presence of turbulence depends upon the main opacity sources in the disk 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 1-D turbulent disk models that have detailed modeling of growth and drift of dust particles. Given their distributions, we recalculate 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"?

Disk Evolution Models [15-16]

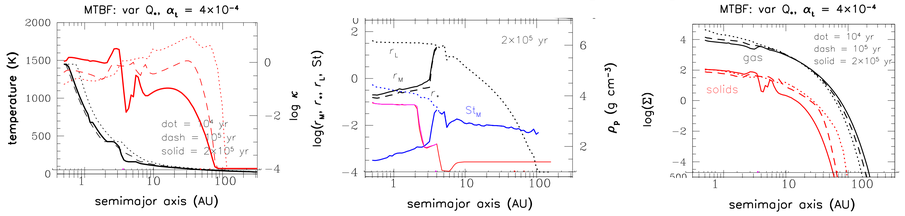


Figure 4. Study undertaken to examine detailed growth of particles in simplified 1-D disk models with turbulence modeled using aformentioned alpha-disk modeling. Above snapshot shows state of disk after 200,000 yrs after formation. Mean temperatures, surface densities and dominant particle masses (indicated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

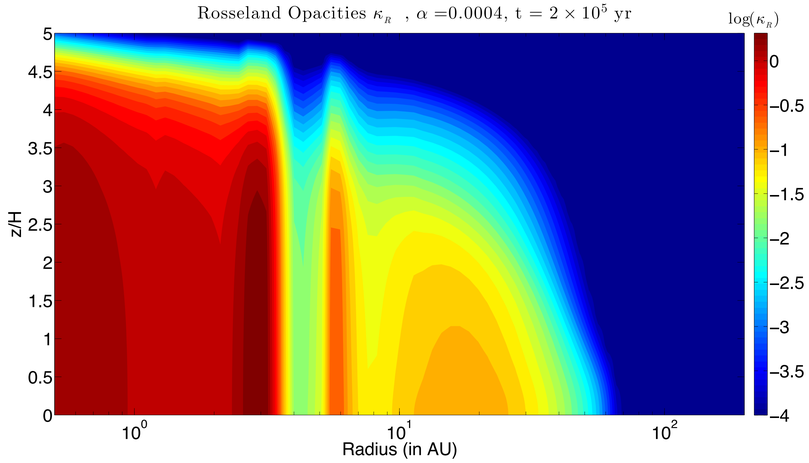


Figure 5. Turbulent Rosseland mean opacities given in units of cm²/gm. Degree of turbulence is given by $\alpha = 4\times10^{-4}$. This figure derived from results of Fig. 4.

Turbulence, Where? A Butcher's Diagram

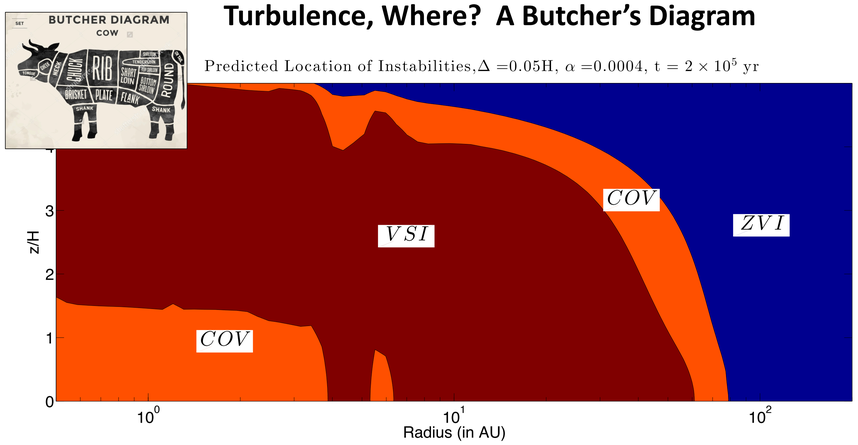


Figure 6 As derived from 1D disk evolution models (Fig. 4). The mutually exclusive cooling-time/opacity requirments of the 3 primary turbulence mechanisms means that any one part of a pp-disk DZ has some turbulent activity. Time corresponds to 200,000 yr. and Δ Indicates scale of turbulent dynamics (in terms of scale height H). Degree of turbulence $\alpha = 4\times10^{-4}$.

Notes and references: [1] SSD NASA Ames Research Center (MS 245-3), Moffett Field, CA, [2] SETI Institute, Mountain View CA – email: orkan.m.umurhan@nasa.gov. [3] Turner, N.J. et al. (2014) *Proto- stars and Planets VI*, 411. [4] Cuzzi, J. N. & Weidenschilling, S. J. (2006) *Meteoritics and the Early Solar System II, 353*. [5] Richard, S. et al. (2016) MNRAS 456, 3571. [6] Umurhan, O.M. et al. (2016) 47th *LPSC*, Abs. #2887. [7] Nelson, R. P., et al. (2013), MNRAS 435, 2610. [8] Lin, M.-K., & Youdin, A. N. (2015) ApJ, 811, 17. [9] Umurhan, O. M. et al. (2016) A&A, 586, A33.[10] Marcus, P.S.; et al. (2015) ApJ, 808, id 87. [11] Lesur, G.R.J & Latter, H. (2016) A&A 462, 4549. [12] Klahr, H. & Hubbard A. (2014) ApJ 788, 21. [13] Lyra, W. (2014) ApJ 789, 77. [14] Latter, H. N. (2015) MNRAS 455, 2608. [15] Estrada, P. R. et al. (2016) ApJ, 818, 200. [16] Estrada, P. R. & Cuzzi, J. N. (2016) 47th *LPSC*, Abs.#2854. [17] Lesur, G. & Papaloizou, J.C.B. (2010) A&A 513, 60.

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