THEORETICAL DEVELOPMENTS ON HYDRODYNAMIC ACTIVITY IN PROTOPLANETARY DISK DEAD ZONES., O. M. Umurhan[1,2], P. R. Estrada[1,2], J. N. Cuzzi[1], [1]NASA Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, SETI, Carl Sagan Institute, Mountain View, CA 94043, (orkan.m.umurhan@nasa.gov)

Abstract: Theoretical advances on the dynamical nature of protoplanetary disk (pp-disk, hereafter) Dead Zones (DZ) have several important implications for the accumulation and evolution of planetesimal dust. This presentation reviews the current state of understanding of fluid dynamical processes, possibly turbulent, operating in DZ's Most of the mechanisms discussed critically depend on the thermal distribution and cooling times of the disk. Given recently developed and published global pp-disk models, we pin-point which mechanism operates in which part of the disk for a given evolutionary epoch of the pp-disk and what qualitative effect they will have upon the kineamatics of planetesimals. The opacity and the temperature distributions in many published global disk models depend upon the parametrization of the turbulent stresses thought to be present. Turbulent stresses are often represented in these model by a classic $\alpha-$disk parametrization which assumes these stresses are released in the disk both steadily and uniformally. Realistic disks exhibiting any one (or a combination) of these dynamical processes will have turbulent stresses that are distributed in both space and time which, in turn, will affect the thermal and cooling-time properties of the disk as well as the concentration of dust. We show progress in work that considers modifications of pp-disk temperature and opacity profiles in radially localized pp-disk sections when the space-time distributions of the turbulent stresses associated with the vertical shear instability are included. We assess the conditions in the properties assessed results in the quenching or shutting-off of the underlying mechanism and possibly indicating limit-cycle behavior.

Introduction: The last ten years has seen a explosion of theoretical interest in the dynamical state of the pp-disk DZ's [1]. Their importance hinges on the expectation that bulk of planetesimal growth likely takes place within these relatively quiescent regions of disks. The degree to which the flow is disordered directly effects the quality of and degree to which planetesimal growth occurs -- and for how long. Over these past ten years DZ's have gone from being considered absolutely inactive to now possibly harboring a whole suite of dynamically active processes involving, to varying degrees, the influence and interaction between disk gas and dust particles. These processes include those that are classical linear instabilities of Keplerian and near-Keplerian flows as well as non-modal growth mechanisms. The former category includes the dynamics of the subcritical baroclinic instability (SBI), the Rossby wave instability (RWI), the vertical shear instability (VSI) the Zombie vortex instability (ZVI), Convective overstability (CO), the elliptical instability (EI), and the streaming instability (SI) – a summary is found in [2] and also see [3].

In this presentation we review these various mechanisms and how they relate one another within a proposed hierarchical framework. For example, CO and VSI are bonafide linear instabilies involving purely gaseous stratified flows with very weak or entirely absent departures from a pure Keplerian state while EI, ZVI and the SBI involve either large amplitude disk perturbations or significant departures from a purely Keplerian state to become active. Given this observation, it is important to assess under what conditions or what plausible scenarios give rise to the conditions for these processes to be active and during what epoch during disk evolution. The overarching concern is to assess both to what degree these various processes are active -- including its impact on dust concentration [4,5,6] -- and what is the resulting turbulent intensity, typically parametrized by the so-called α parameter [1]. We will present some early results identifying where one might expect which mechanism to operate in global disk models both published and currently in development [4,5].

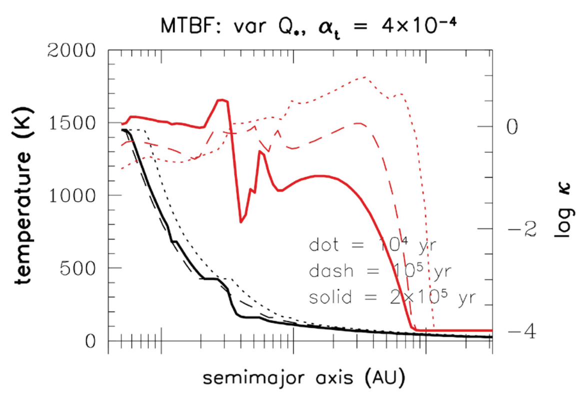

Fig. 1. Temperature and opacity profiles at various epochs taken from a recently announced global disk model [4]: Red/black curves denote opacity/temperature. The opacity and temperature profiles of this particular model are conducive to the VSI.

Thermal/Opacity profiles: Moreover, many of the aforementioned mechanisms sensitively depend upon the effective thermal cooling/relaxation times associated with the active modes because thermal effects will determine whether or not the instability/process of interest manifests itself at all. For example, the degree to which the CO, VSI and ZVI are active depends – in one way or another -- upon the vertical entropy profile in the disk as well as the thermal cooling/response times associated with the active modes of the process in question.

An interesting case in point is the mutual complementarity of the VSI and the ZVI, the former requires extremely short cooling times while the latter requires nearly adiabatic disturbances to operate. It was shown in [7] based on appropriate radial length scales for the VSI to operate requires the disk opacity $\kappa < 1$ cm^2/gm. The ZVI, on the other hand, requires extremely long cooling times and for the length scales appropriate for it to (which are similar to the VSI) operate can be conservatively estimated to be for when $\kappa > 50$ cm^2/gm. **Fig. 1** shows a sample global (but by no means the only possible) disk model recently developed assuming a globally uniform α distribution which concurrently follows the evolution of dust size. Judging by the predictions of this model, the opacities of the disk are such that the VSI is expected operate during latter times of the disk evolution (after 10^5 yr). Other global disk models predict locations in the disk where the opacity satisfies the $\kappa > 50$ cm^2/gm criterion for the ZVI to operate.

Similar preliminary considerations such as these will be presented to map out the locations in the disk where these instabilities, as well as the others mentioned in the Introduction, might operate.

Dynamical influence and back-reaction: Using the VSI as a case-study, we can examine how the velocity field and unsteady stresses can back-influence the temperature profiles in the disk by effecting the turbulent concentration/location [6] of the dust and places where heat (due to unsteady activity) is released. Recent studies [8] show that modifications of the vertical temperature profile can limit or, even, turn off the VSI altogether. We investigate this possibility and construct an iterative procedure to update global disk model solutions like that in [4].

For example, **Fig.2** shows the results of an axisymmetric model of the VSI in a developed state (in the shearing box). **Fig.2c** shows the resulting distribution of the Reynolds stress showing that the unsteady activity is located above and below the midplane. If the resulting turbulent heat release is strong there, resulting in a significant positive temperature gradient, it might lead to the shut-down of the instability. However concurrently, the passively advected dust particles, which are primarily responsible for the opacity variations in the disk, will settle down toward the midplane as the strong vertical velocity fields that arise due to the instability (see **Fig.2a**) would vanish. This can lead to limit-cycle behavior since the temperature profile would return to a state favorable to the VSI [9]. The extent to which this happens will be examined in some detail. The vertical stirring/collection of the dust will be also guided by the strength and steadiness of the azimuthal vorticity field, as shown in **Fig 2b**. This work is in development.

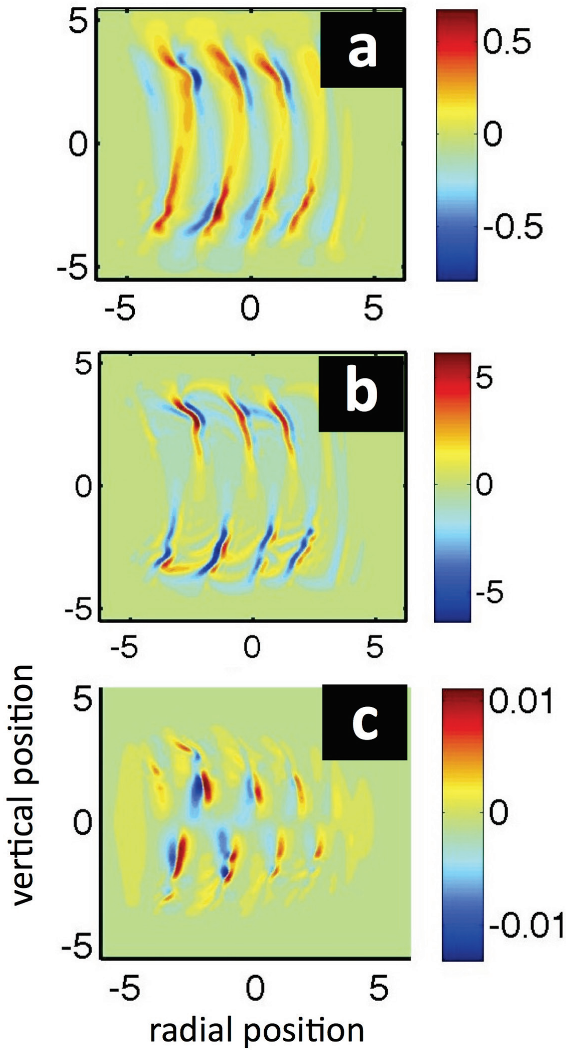

Fig. 2. Cylindrically symmetrick shearing box model of the VSI. Radial (r) and vertical (z) lengths scaled by local disk scale height. (a) Vertical velocity, (b) azimuthal vorticity (c) Reynolds stresses. Unsteady stresses focused near $z = \pm 2$.

References:. [1] Turner, N.J. et al. (2014) *Protostars and Planets VI,* 411. [2] Richard, S. et al. (2015), (arXiv:1601.01921) , [3] Marcus, P.S.; et al.. 2015; ApJ 808, id 87; [4] Estrada P., Cuzzi J., Morgan D. 2016 ApJ, in press (arXiv:1506.01420); [5] Estrada, P. and Cuzzi, J.N., LPSC – XLVII (2015, this conference). [6] Cuzzi, J.N. et al. LPSC – XLVII (2015, this conference). [7] Nelson, R. P., et al. (2013), MNRAS 435, 2610. [8]Lin, M.-K., & Youdin, A. N. (2015), ApJ, 811, 17. [9] Stoll, M. H. R., & Kley, W. 2014, A&A, 572, A77