ARE THE FIRST PLANETESIMALS BORN IN TURBULENCE?

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Introduction: Several lines of evidence from analysis of the meteoritic record suggest that the cores of the giant planets -- including Jupiter -- were formed in the first 0.5 Ma. It must therefore mean the first planetesimals (~70-100 km in size) must have found a way break the known various cm-m barriers to growth within that time frame. A leading candidate to leapfrog past this obstacle is the Streaming Instability (SI). The SI is effective at generating strong overdensities, which can efficiently generate subsequent "pebble-cloud" gravitational collapse if the particle 0.04< St < 0.2 and Z > 0.015 [1,2] – in which St = $\tau_s\Omega$, where τ_s is the particle stopping-time and Z is the local disk metallicity. However two serious issues stand in the way: Several lines of theoretical and computational evidence shows that the magnetically inactive Ohmic zones of the solar nebula are susceptible to several hydrodynamic instabilities which drives moderate levels of turbulence ($5\times10^{-5} < \alpha < 10^{-3}$) [3], which suppresses the SI [4], where α measures the degree of turbulence. Furthermore, global evolution models of particle growth in the solar nebula [5] predict that particle St struggles to get past 0.01, which again makes it difficult for the SI to operate effectively -- except perhaps near the H_2O ice snowline [e.g., 6]. Another path toward generating gravitationally bound particle overdensities in turbulent flows is Turbulent Concentration, e.g., recently examined by [7].

Aims, Methods and Setup: [3] show that there may be locations in the disk in which none of the hydrodynamic instabilities are operative. Therefore particles should settle onto the midplane and perhaps become turbulent on their own accord. If their properties are such that the SI is not expected to be operative then it is important to study how those settled layers dynamically respond. We utilize the community PENCIL code to execute detailed simulations of midplane settling particle layers under two conditions in which the SI is not expected to operate, namely Z=0.01 with St = 0.04, 0.2 [1]. There is no external source of turbulence. 3D simulations are run with 128^3, 256^3 and 512^3 grid elements. The simulation box is $(0.2\ H_g)^3$, where H_g is the gas pressure scale height. Settling particle layers will be characterized by a value of the midplane mass volume density ratios, $\varepsilon \equiv \rho_d/\rho_g$. H_p is the particle scale height.

Key Results: We find that settling particle layers setup strong vertical gradients in the mean radial and perturbation azimuthal velocity fields [u_g,v_g', respectively] consistent with earlier unpublished findings [8]. The Fjorthoft-Rayleigh criterion for Kelvin-Helmholtz (K-H) roll up is met by u_g when ε=1 at the midplane (black arrows designating $\mathfrak{F}$ in Fig A). K-H roll-up occurs for axisymmetric disturbances and develop very short timescales (~Ω^{-1}), unlike previous claims suggesting that transition mainly occurs for non-axisymmetric disturbances and on relatively long time scales (10's Ω^{-1}) [9-10]. Moreover, we find that that K-H action occurs primarily in layers where little-to-no particles are present (i.e. 2-3 H_p from midplane) and appears to be a significant sourcing of turbulent churning for the midplane particle layer (Fig B).

Furthermore, we find that that the vertical gradient in v_g' leads to the generation of the so-called symmetric instability (SyI), well known to drive mixing-dynamics in submesoscale modeling of the oceans and atmosphere [e.g., 11]. The SyI becomes strong once Ri<1, suggesting that it becomes active first before the K-H instability, the latter which classically requires (Ri<1/4) – where Ri is the Richardson Number. The growth timescales of the SyI are fast-acting comparable to K-H above (i.e., ~Ω^{-1}, Fig. C) when the Ri < 1. The instability develops into radially thin nearly axisymmetric structures in vorticity and other fluid quantities (Fig Da). Moreover, we find that the particles respond to the SyI fluid pattern and do not appear to be the primary driver of its emergence (Fig Db). We think this dynamic is responsible for the Ri<1 criterion reported for the suite of particle gas simulations in [12]. We suspect these findings are contained within the general framework of [13].

We have conducted some long time model runs at 128^3 resolution for both St considered. While we find that the SI is at best weakly and only intermittently expressed for St = 0.2, surprisingly we find that after a very long period of time in the St = 0.04 experiment a radially-drifting pronounced patterned state appears in Z (Fig. E). Whether or not this is due to the SI somehow emerging out of the turbulent state or if it is an expression of some kind of self-organized criticality from within the turbulent state remains to be understood.

Finally we have calculated the kinetic energy spectrum for our highest resolution run (512^3, St = 0.2) where we find the level of turbulence to be $\alpha<8\times10^{-6}$ (Fig. F). We surprisingly find that the kinetic energy of the gas is sapped by the particles at a critical length scale $\lambda_c \equiv 2\pi/k_c \cong 0.005\ H_g < H_p$, in which λ is the length scale of a turbulent eddy. The gas turbulent energy spectrum per unit gas mass, $E_g(k)$, exhibits ~ $k^{-6/5}$ up to k_c, beyond which E_g plummets while the corresponding power spectrum for the particles becomes dominent (Fig F). Interesingtly, we find that the axisymmetric collapsed spectrum shows a $k^{-11/5}$ dependence out to values of k greatly exceeding k_c, which harkens to the well-known Obukhov-Bolgiano scaling identified for stably stratified turbulent flows [14] (to be discussed at meeting and other findings).

Are Planetesimals Born in Turbulence?: Even though the SI is not formally active in the above high resolution run, the particle density field in the settled turbulent state exhibits small scale high density fluctuating filamentary structure (shown at time of meeting) – strongly reminiscent of structures known to emerge under conditions where the SI is obviously manifest [2]. Taken together with the concerns in the Introduction, we openly conjecture if whether or not the first planetesimals – if formed away from the snowline, for example – were formed under the complex conditions of turbulence, whether externally driven or self-generated by the settled particle layer. We will present a complete suite of arguments at the time of the meeting.

References: [1] Carrera, D. et al. (2015) *A&A* [2] Nesvorny D. et al. (2019) *Nature Astronomy 3*,808. [3] Pfeil T. and Klahr H. (2019) *ApJ 871*, 150. [4] Umurhan O. M. et al. (2020) *ApJ 895*, 4. [5] Estrada, P. R. et al. (2016) *ApJ 818*, 200. [6] Hyodo R. et al. (2021) arXiv:2012.06700. [7] Hartlep T. and Cuzzi J. N. (2020) *ApJ 892* , 120. [8] Ishitsu, N. et al. (2009) arXiv:0905.4404v1. [9] Johansen A. et al. (2006) *ApJ 643*, 1219. [10] Barranco J. A. (2009) *ApJ 691*, 907. [11]Stamper M. A. and Taylor J. R. (2017) *Ocean Dynamics 67*, 65. [12]Gerbig K. et al. (2020), *ApJ, 895*, 91. [13] Lin, M.-K. (2020) arXiv:2011.12300. *579*, A43. [14] Alexakis A. and Biferale L. (2018) *PhR, 767*, 1.