Turbulent Clustering of Protoplanetary Dust and Planetesimal Formation. L. Pan[1] and P. Padoan[2], [1]School of Earth and Space Exploration, Arizona State University (P.O. Box 871404, Tempe, AZ, 85287; liubin.pan@asu.edu), [2]ICREA & ICC, University of Barcelona (Marti i Franques 1, E-08028 Barcelona, Spain; ppadoan@icc.ub.edu).

Introduction

Solid Particles are dragged by turbulent gas motions into dissipative trajectories, resulting in the formation of dense particle clusters, even if the gas flow is incompressible. This clustering process may have important effects on the growth of dust particles in protoplanetary disks, and may even help the formation of planetesimals [1,3]. However, its properties are not completely understood, particularly its Reynolds number dependence, and the clustering of large particles, coupled to turbulent motions of inertial-range scales. We address this problem by study turbulent clustering with large numerical simulations, and then discuss the relevance of our results for models of planetesimal formation [1,2,3].

Results

Using numerical simulations, we compute the radial distribution function (RDF), which measures the probability of finding particle pairs at a given distance, and the probability density function (PDF) of the particle concentration [4]. These clustering statistics depend on the Stokes number, *St*, that is the ratio of the particle friction timescale, τ_p, to the Kolmogorov timescale (the shortest timescale in a turbulent flow, corresponding to velocity fluctuations at the dissipation scale). Small particles have short friction times, hence small *St*, and couple to gas motions on small, dissipative scales in the turbulent flow. Large particles, with longer friction times and larger *St*, couple to larger scales in the inertial range of the turbulence.

We find that, for the small particles coupled to motions in the dissipation range, the clustering intensity strongly peaks at $St \simeq 1$, and the RDF of $St \simeq 1$ particles shows a fast power-law increase toward small scales. This indicates that the clustering amplitude continues to grow towards smaller scales, possibly all the way down to the Browinian scale, which should considerably enhance the collision and growth rates of protoplanetary dust grains (~ 100 μm, depending on disk parameters). However, in a recent model of planetesimal formation [1,2], based on turbulent clustering of chondrule-size particles, the probability of finding strong clusters that can seed planetesimals may have been significantly overestimated.

The clustering of larger particles at inertial-range scales is of particular interest to the problem of planetesimal formation. Clustering of these particles occurs primarily around a scale where the eddy turnover time is $\sim \tau_p$. We find that particles of different sizes tend to cluster at different locations, leading to flat RDFs between different particles at small scales (no growth of clustering amplitude towards smaller scale). Therefore, in the presence of multiple particle sizes, the overall clustering strength decreases as the particle size distribution broadens. In general, the turbulent clustering amplitude of such large particles (for example m-sized boulders in protoplanetary disks), is much lower than for small particles with $St \simeq 1$, as shown by their cumulative PDFs. However, we cannot rule out yet that the turbulent clustering of these particles may give a significant contribution to the formation of planetesimals, because even larger simulations are needed to measure reliably the dependence of their clustering on Reynolds number (the Reynolds number of protoplanetary-disk turbulence is orders of magnitude larger than what can be achieved in numerical simulations).

References

[1] Cuzzi, J. N., Hogan, R. C. & Shariff, K. 2008, ApJ, 687, 1432
[2] Johansen, A., Oishi, J. S., Low, M.-M. M., Klahr, H., Henning, T., & Youdin, A. 2007, Nature, 448, 1022
[3] Chambers, J. E. 2010, Icarus, 208, 505
[4] Pan, L. and Padoan, P. 2011, ApJ, in press

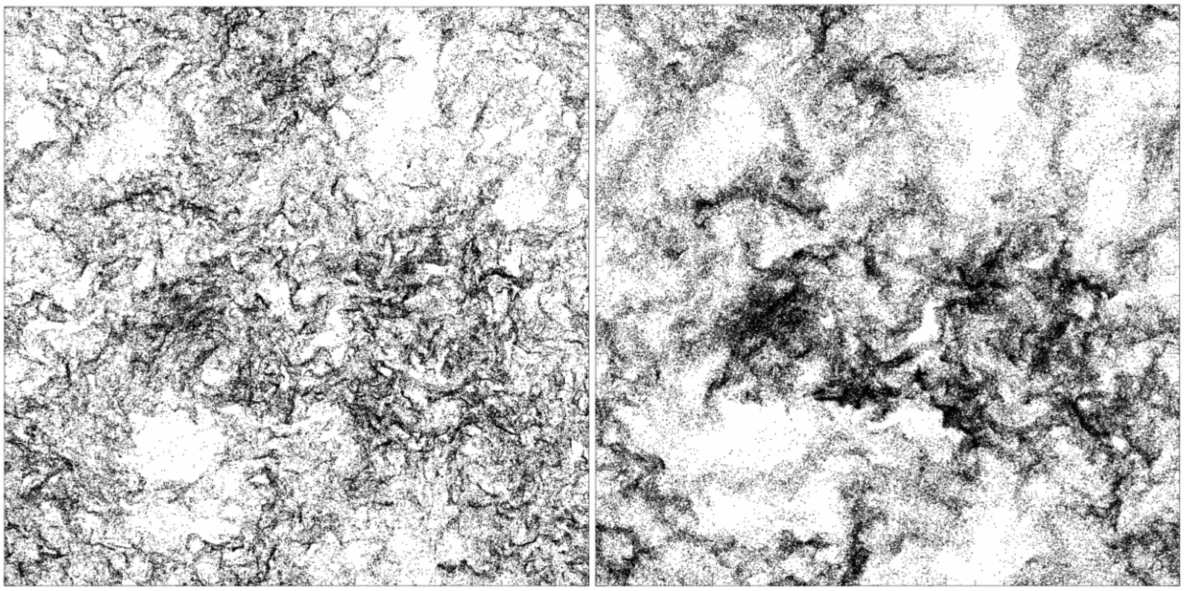

Figure: Positions of all the particles with *St*=1.2 (left panel) and *St*=4.9 (right panel) within a thin slice of thickness equal to 2% of the computational box. Density fluctuations are much stronger for particles with *St*=1.2 than for those with *St*=4.9, but this cannot be fully appreciated from the images, due to the overlap of particle positions. Notice the very small scale structures present in the spatial distribution of the *St*=1.2 particles. Dense particle filaments and large voids can be seen in both panels, with sizes approaching the integral length of the flow, estimated to be approximately 0.2 times the computational box size. The estimated size of the dissipation scale, η, is approximately 10^{-3} times the box size.

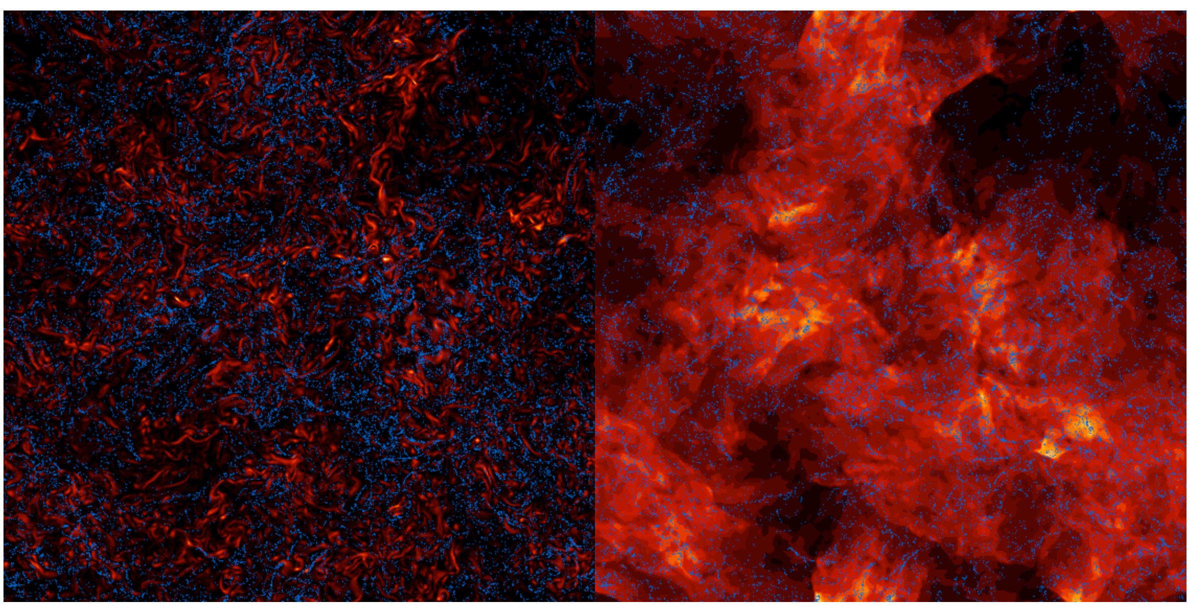

Figure: Flow vorticity (left panel) and density(right panel) on a slice of the simulation box. The thickness of the slice is two computational zones. The color scale is linear with vorticity or density, and the red color represents high vortcity or density values. Blue dots are locations of particles with *St*=1.2. A clear anti-correaltion is seen between the vorticity field and the particle positions, whereas the particle distribution is independent of the flow density. The total number of particles is the same in the two panels.