STUDIES OF GAS-PARTICLE INTERACTION: IMPLICATIONS FOR THE STREAMING INSTABILITY IN PROTOPLANETARY DISKS

Holly L. Capelo[1], Haitao Xu [1], Michiel Lambrechts[2], Anders Johansen[2]& Eberhard Bodenschatz[1]
[1]*Max Planck Institute for Dynamics and Self-Organization (MPIDS), 37077 Göttingen, Germany*
[2]*Lund Observatory, Lund Sweden*

Abstract We present the early results from a novel experiment to study a particle-laden flow, under a parameter regime relevant to the conditions in planet-forming systems. We investigate the gas-particle interactions to identify the presence of and details regarding the streaming instability, which is theoretically predicted to aid the coalescence of small dust grains to form planetesimals - the macroscopic objects that will eventually interact gravitationally and become planets. We vary properties of the system such as dust-to-gas ratio, relative particle-gas velocity and gas pressure, for comparison to numerical simulations of protoplanetary disks. Experimentally calibrated numerical calculations of the particle motion within the instability regions will be used to model the evolution of protoplanetary disks at the scale of small dust grains, representing an unprecedented precision in our understanding of these difficult to study systems.

INTRODUCTION

It is believed that planets form out of gas and dust particles present in circum-stellar accretion disks [10, 14, 2]. The observationally determined lifetimes of such disks is typically 3-10 Myr [11]. This relatively short timescale sets constrains on the processes that underly the growth of macroscopic objects in the disk. At sizes smaller than decimeters, dust particles agglomerate via collisions. However, the growth of dust agglomerates to ever-larger bodies cannot proceed by collisions alone [4, 6, 16]. It has further been shown that objects that are weakly coupled to the surrounding gas drift rapidly into the parent star, depleting the disk of solids within 0.1 Myr. This radial-drift effect is most pronounced for objects around 1 m in diameter, further exacerbating the limitations to growth past intermediate sizes [1]. A promising solution to this set of issues involves a gas-dust streaming instability (SI), which produces large local dust-density enhancements. The high-density regions subsequently become gravitationally unstable and collapse directly into 100 km-sized planetesimals, within the timescale set by radial drift [15, 8, 13, 7]. The SI arrises principally from the difference in orbital velocity between the gas and the dust particles (henceforth relative velocity). Whereas dust particles' orbits follow simple Keplerian dynamics, the gas component of the disk responds to the temperature and density gradients emanating from the central star, thereby receiving extra pressure support against gravity. The gas therefore orbits at a slower, or sub-Keplerian, velocity, resulting in drag on the dust particles [3, 2]. The presence of a SI is then owing to collective drag effects on multiple dust particles. Current numerical simulations cannot simultaneously capture the large-scale disk behavior and the details of the small-scale physics within the dust-enhanced regions. It is our goal to improve the models for planetesimal formation via collective dust-aggregate effects by calibrating and validating such simulations with our laboratory experiments. Simulations of the SI, both on scales characteristic of protoplanetary disks and on that of the experiment, are underway, using a custom version of the publicly available Pencil Code [5]. Below we explain the design and purpose of a new experiment, intended to produce reliable predictions on simulation parameters, such as the local concentration of dust aggregates and their collision velocities.

EXPERIMENTAL SETUP

By analogy to the relative velocity between the gas and dust particles in a disk, we are studying a particle-laden stream in the laboratory, with emphasis on the effect of particle-settling velocities. In this experiment, the dust particles fall vertically under the effect of gravity, in opposition to an upward-directed, low-pressure gas stream. Stereoscopically arranged high-speed cameras record the particle motion, yielding particle velocities, accelerations and local concentrations via the image analysis [9, 12]. In figure 1, the experimental setup is demonstrated, where the upward gas stream acting against the tendency of the particles to fall is analogous to the net relative velocity expected to be experienced between the gas and dust particles in the disk. The base contains a porous filter which produces a pressure drop from atmospheric pressure outside the device to 1 millibar inside of the apparatus. The particles, of approximately 100 μm glass or plastic beads, are preloaded into the chamber and are effectively suspended in and/or circulating throughout the flow. By varying the follow rate, porosity of the filter material, or the choice of gas, we can vary the density/pressure and relative particle-gas velocity to establish which conditions are conducive to the SI effect. This project is currently in its first year, in which we are constructing and testing the apparatus prototype, with the first quantitative results expected in Spring/Summer 2013. Our experimental results, once analyzed and properly scaled, will produce useful inputs for the complimentary numerical aspects of the collaboration.

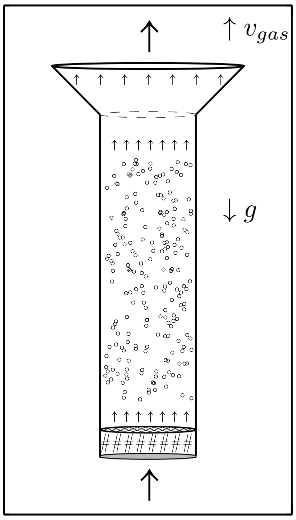

Figure 1. Sketch of the experimental setup. Dust particles subject to gravity are suspended in a vertical, dilute gas stream (indicated by arrows) in a clear tube, such that cameras can record the particle positions to determine their sedimentation velocities and concentrations. The dimensions of the apparatus are diameter $\approx$ 10 cm, height $\approx$ 1m. The base is filled with material of porosity coefficient, $\alpha \approx 0.08 \times 10^{-12}$ m^2, enabling a pressure of 1 mbar to be achieved for a 1 m s^{-1} flow rate.

NUMERICAL SIMULATIONS

Similar to the configuration of the experiment, two-dimensional simulations track particles falling at terminal velocity through a fluid. The reduced system of equations for the particles and the incompressible fluid are recast in a non-rotating (absent of Coriolis forces), center-of-mass frame. Early results show that small-amplitude particle-density waves exhibit an instability similar to that seen in previous SI simulations that include rotation, i.e. the fluid settles into a turbulent state which leads to particle clumping. On-going efforts with these sets of simulations includes extending them to three dimensions, and moving from the current choice of periodic boundary conditions to include wall effects, in order to more realistically model the experiments.

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