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Approaching Preplanetary Streaming Instabilities in Laboratory Experiments

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Abstract

Streaming instabilities are an important particle concentration mechanism in protoplanetary disks but the idea is solely based on numerical simulations so far. We carried out first experiments to approach this mechanism in laboratory studies. We observed a particle cloud trapped in a rotating system under Earth's gravity. The experiment Stokes number is 0.0024. For average dust-to-gas ratios up to 0.02 particles behave like individual test particles. The sedimentation speed is identical to the calculated one. For larger dust-to-gas ratios the motion of particles gets sensitive to particle density and interparticle distances. This suggests a self-amplification of a denser region and provides a first step in supporting the concept of streaming instabilities.

1. Introduction

A major issue in planet formation theory is the radial-drift barrier. Solid particles in a protoplanetary disk would orbit around a star with Keplerian velocity, but the pressure-supported gas is about 50 m/s slower. This results in an aerodynamic drag and the headwind causes the solids to spiral inwards.

Streaming instabilities introduced by Youdin and Goodman (2005) are a promising way to overcome this barrier. In this mechanism, the drag produces a back reaction on the gas, leading to an increase in the gas velocity and a reduction of the aerodynamic drag. It has been shown in simulations, that this aerodynamic coupling between the gas and the particles can lead to clustering and a collective drag reduction and finally to the formation of planetesimals (Johansen and Youdin 2007; Yang et al. 2017).

In analogy to the relative velocity of dust and gas in a protoplanetary disk, we investigate spherical sedimenting particles trapped in a rotating cylindrical vacuum chamber at low pressure.

2. Experiment

2.1 Setup

The experiment chamber is 20 cm in diameter and is evacuated to a preset pressure at the beginning of the experiment. Inside the chamber a ring of LEDs generates light that is scattered from the particles which are imaged by a camera in the front. The particles are generated through a vibrating sieve, included in an extension of the vacuum chamber. This beam of particles has a width of 25 mm and a thickness of 5 mm. Particles are injected while the experiment is still at rest to fill the regions that allow stable (circular) particle trajectories once the rotation is started. A sketch of the experiment can be seen in fig. 1.

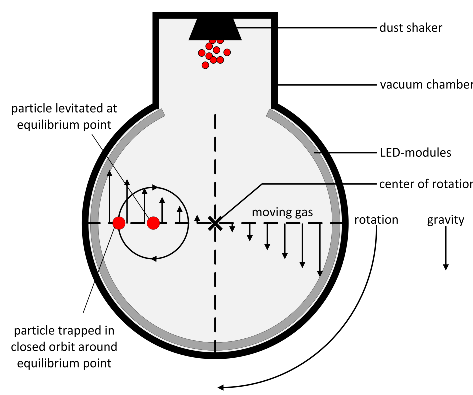

Figure 1: Schematics of the experiment. Not shown are auxiliary parts. The experiment chamber is a vacuum chamber evacuated prior to experiments to a preset pressure. A camera is observing particles from the front by scattered light.

2.2 Experimental parameters

For this first study we used hollow glass spheres to allow large non-sticky particles with low density for short gas-grain coupling times. The grains have an average diameter of 165 µm and a friction time of 7 ms. As gas we used air with a gas pressure of 2100 Pa.
We analyse the sedimentation velocity of the particles with respect to the average dust-to-gas ratio. Moreover, we defined the closeness C_i of particle i as

$$C_i = \sum_{n=1}^{N} \frac{1}{r_n - r_i} \tag{1}$$

to get an insight on local particle number densities. Be aware that the closeness is constructed from the distances between the individual particles $(r_n - r_i)$ and the total number of particles N. The dependence of the sedimentation velocity on the closeness is an indicator for a collective behaviour of the particles.

3. Grain Motion

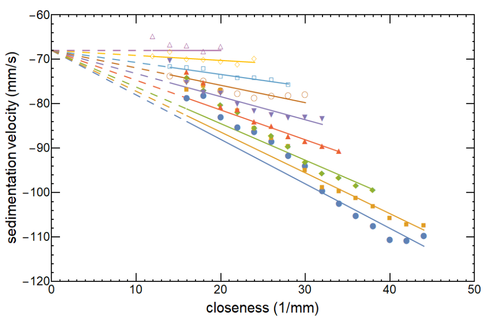

Figure 2: Sedimentation velocity over closeness for individual rotations of the experiment. The evolution within the experiment chamber goes from initially dense (lower data, 2nd round) to less dense (upper data, 10th round) cloud as particles diffuse to the chamber wall. Data are average values for typically several hundred particles

Particles in regions with high closeness sediment much faster than particles in less close regions as seen in fig. 2. This figure shows the values averaged over full rotations of the experiment, therefore increasing in time from 3 s (lower curve) to round 10 or 30 s (upper curve).
Visible in round 10 (fig. 2), particles at later times, on average in a less dense cloud, all sediment with the same speed even at a closeness 20 mm^{-1}. In contrast, in the high loading case, the speed of particles with the same closeness 20 mm^{-1} is increased. The speed is no longer constant but now depends on the closeness. Obviously the system is sensitive to closeness variations in this case. To a good approximation the dependence of the sedimentation speed on closeness can be described as linear or

$$v = v_0 - F_s \cdot C_i \tag{2}$$

The sensitivity factor F_s increases with the average solid-to-gas-ratio of the system above a threshold solid-to-gas ratio of 0.02. Below this value particles behave like individual grains independent of the closeness.
For dust-to-gas ratios above 0.02 particle motion does depend on closeness and shows much higher sedimentation speeds than individual grains.

For the high mass loading individual particles can change their motion by entering regions of high closeness, speeding up. However, they can also drop out again into a region of lower closeness. We do not see any concentration effect leading to a continuous local increase of particle density for longer than a few seconds.

4. Summary and Conclusions

For solid-to-gas ratios above 0.02 we see a collective behaviour of the particles. The sedimentation velocity of the dust grains depends on both, the closeness and the average solid-to-gas ratio. Overall, our experiments support - for the first time in laboratory research - the ideas underlying streaming instabilities.

Acknowledgements

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References

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