

Dense Particle Clouds in Laboratory Experiments in Context of Drafting and Streaming Instability

Studying the Transition from Single Particle to Collective Particle Behavior in the Knudsen regime.

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Abstract The streaming instability, as an example of instabilities driven by particle feedback on a gas flow, has proven to play a major role in controlling the formation of planetesimals. Collective feedback via friction from particles to the gas flow, in which they are embedded, is known to trigger instabilities has proven to play a major role in controlling the formation of planetesimals. These instabilities in protoplanetary disks occur at the transition from gas dominated to dust and ice particle dominated. Here, we present experiments to approach this situation in the laboratory for particles in the Knudsen flow regime. In this experiments, we observe a particle cloud trapped for about 30 seconds in a rotating system under Earth's gravity. For average dust to gas ratios up to 0.08, particles behave like individual test particles. Their sedimentation speed is identical to that of a single free falling particle, even in locally denser regions. However, for higher dust to gas ratios, the motion of particles becomes sensitive to clumping. Particles in locally denser regions now sediment faster. Their sedimentation speed now depends linear on the overall dust to gas ratio. This clearly shows a transition from tracer like behavior to collective behavior. Beyond this findings, these types of experiments can now be used as a gauge to test the particle feedback models in astrophysical hydro codes which are currently used for numerical simulations of streaming instabilities.

Keywords

1 Introduction

In the core accretion model for planet formation, dust first has to be converted to kilometer sized planetesimals, which then accumulate via gravitational interaction into planetary embryos, the precursors of terrestrial planets as well as gas and ice giants. In the standard scenario, terrestrial planet formation starts from dust which is evolving through all size scales. Initially, dust growth is driven by mutual collisions (Blum & Wurm, 2008). However, this growth gets stalled either at the drift barrier (Weidenschilling, 1977), the fragmentation barrier (Birnstiel et al., 2012) or the bouncing barrier (Zsom et al., 2010; Kelling et al., 2014; Kruss et al., 2016, 2017).

One way to continue evolution is the gravitational collapse of the particle layer in the disk (Safronov, 1969; Goldreich & Ward, 1973). Dense particle layers with local dust to gas ratios of unity and above are subject to instabilities (Weidenschilling, 1980) driven by the mutual coupling between gas and particles, which have an incommensurable equilibrium state (Nakagawa et al., 1986). These instabilities can be generalized as Resonant Drag Instabilities (Squire & Hopkins, 2018), of which the streaming instability plays a major role in regulating the onset of gravitational collapse (Youdin & Goodman, 2005; Johansen et al., 2015; Simon et al., 2016; Schreiber & Klahr, 2018). Only if particles are concentrated to the point where self-gravity starts to dominate over turbulent diffusion km-size planetesimals can form by gravitational collapse (Johansen et al., 2007, 2011; Johansen et al., 2015).

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In general the numerical simulations show that high solid-to-gas ratios are required and that the gas-grain coupling times have to be comparable to the orbital timescales. E.g. Bai & Stone (2010a) find the typical dust-to-gas ratio of 0.01 to be insufficient to concentrate solids to the limit of gravitational collapse. In any case, the scenario of gravitational collapse regulated by streaming instabilities is widely accepted as the standard way to connect to and take over from the preceding collisional growth phases of pebbles. However, laboratory experiments are essentially missing.

The situation of a protoplanetary disk can certainly not be set up 1 to 1 in a laboratory setting. However, the motion of a dense cloud of particles over longer timescale can be accessed as described in this paper. It might answer basic questions, like under what conditions are particles only tracers of gas motion or when is a back reaction to the gas notable. Is this really only occurring at a dust to gas ratio of about 1? What are the minimum dust to gas ratios needed to see collective effects? Is there a smooth or a sharp transition? How do density fluctuations develop in experiments? Are they stable or do they grow in amplitude? As numerical codes describing large protoplanetary disks should be capable of reproducing small scale laboratory results, this also offers an opportunity to verify and improve numerical codes. So this is a first work in that direction.

So far, only Lambrechts et al. (2016) hinted at a potential experiment to study particle density fluctuations in the laboratory for sedimenting grains which they simulated in a static gas column. The related experiment was carried out by Capelo (2018). That work studied sedimenting grains in the upward draft of a gas flow on a microscopic level. According to Capelo (2018), sedimentation velocities of particle pairs were affected within an inter-particle distance of 4 mm. Nevertheless, there are issues concerning the small measurement volume giving only a small inside of the experiment vessel of 1 cm³ of the 9 cm diameter tube, generally low particle numbers $\ll 50$ observed, grains with unknown size distribution and shape and the potential influence on continuous wall collisions in various ways.

No other experimental approaches to streaming in low pressure gases are known to the authors.

Having a complex two fluid (particles and gas) problem, it is of highest interest to study in an experiment how particle clouds really react to changing dust to gas ratios.

Usually, experiments on sedimentation are short. Therefore, ways to levitate grains are needed as e.g. the upward draft used by Capelo (2018). We use a different approach here. An experimental setup that allows

the study of particle evolutions for longer time in the laboratory in a more defined way is a rotating cylinder with the cloud of particles and gas within. The rotation axis has to be horizontal. In such a rotating cylinder with no-slip boundaries at the cylinder mantle, the gas motion in equilibrium is simply a rigid rotation together with the cylinder. Solid particles embedded in this cylinder still feel sedimentation. However, if their gas grain friction time is small compared to the rotation time, they can be considered to fall with terminal speed at all times. This terminal speed is always given relative to the gas. As the gas motion depends on the distance from the cylinder axis, ~~so does~~ the absolute motion of the grain ~~vary~~ in the laboratory reference frame. In the up-drift part of the gas rotation, there is a stable point for a sedimenting particle, where its downward sedimentation speed and the upward gas velocity cancel each other. Disturbing a particle from this equilibrium point leads to circular trajectories as shown below. This way particles can be trapped for long time, mostly limited by centrifugal forces as also estimated below. Such an experiment has been used before by Blum et al. (1998) and Poppe & Blum (1997), but for aggregation studies. This setup is inspired by the idea of particle trapping in convective eddies in protoplanetary disks as studied by Klahr & Henning (1997). Details are given in the experiment section.

In a simplified way, the situation that can be studied in the laboratory with the given setup is as follows. A larger grain takes longer to couple to a gas flow than a smaller grain and sediments faster than the small grain. But how many small particles have to be how close to each other to act like a larger grain as suggested by Johansen & Youdin (2007)? And how does increasing the overall dust to gas ratio influence the particle motion in this system? Will "drafting", the attraction of particles in the wake of a particle clump, as outlined by Lambrechts et al. (2016) change the particle density and spontaneously form dense clumps?

Section 2 describes the experiment, its function and basic parameters. In section 3 we outline the basic gas-grain interactions and parameters describing clouds of particles especially in the experiments. We also introduce the closeness as parameter. Section 4 gives the results of measurements of individual particles moving as part of a particle cloud. Section 5 adds some more discussion to the results. Section 6 is a short summary of the most important experimental findings. Being far from perfect we point out the caveats in section 7 and conclude in section 8.

2 Experiment

2.1 Setup

The basic feature of the ground based experiment that prevents particles from sedimenting to the ground is trapping them in circular orbits within an eddy. This idea was proposed by Klahr & Henning (1997) for protoplanetary disks (fig. 1). The same idea applies in our experiment. One difference is that the rotation of the gas is not induced by thermal convection but by the rotation of an experiment chamber. **As the chamber walls apply friction to the gas, it responds by rotating in a rigid rotation along with the vacuum chamber.** Another difference is that in the solar nebula the vertical z component (perpendicular to the disk mid-plane) of stellar gravity changes with height as $g_z = -\Omega_{Kepler}^2 z$, which leads to variations in the settling velocity. **As an effect, sufficiently small particles spiral inwards towards their equilibrium point, which might be mimicked in the laboratory but is not the focus here.**

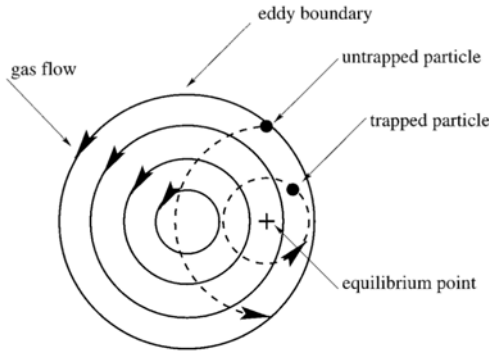


Fig. 1 Principle of particle trapping against gravity in a convective eddy of a protoplanetary disk (Klahr & Henning, 1997).

A sketch of the experiment can be seen in fig. 2.

The experiment chamber is about 22 cm in diameter and 25 cm in depth with the measurement plane in the middle of the chamber. It is evacuated to a preset pressure before the experiment is started. The vacuum pump is then disconnected. A number of electrical contacts are fed through to the rotating system. Inside the chamber a ring of LEDs generates light that is scattered from the particles which are imaged by a non-rotating camera in the front. The particles are injected into the chamber through a vibrating sieve included in an extension of the vacuum chamber. This beam of particles

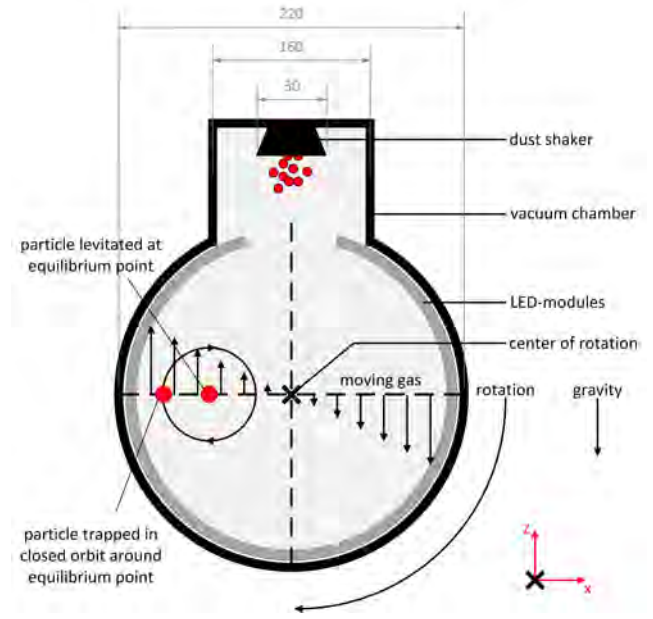


Fig. 2 Schematics of the experiment. Not shown are auxiliary parts. The experiment chamber is a vacuum chamber evacuated prior to experiments to a preset pressure. A camera is observing particles from the front by scattered light. **The origin of the coordinate system is the center of rotation.**

has a width of 5 cm and a thickness of 5 mm. **Particles are falling into the chamber while the experiment is still at rest. This fills the regions with particles that are stable once the rotation is started.** After the onset of rotation, the injection mechanism is stopped. A camera is observing the particles from the front at a distance of approximately 45 cm. The frame rate of the camera is 100 fps and the exposure time is 1800 μ s. The field of view is 16x13 cm and the depth of field is 5 cm. Real particle tracks can be seen below in fig. 6.

Observations were taken for 30 s resulting in about 1 million particle positions. Image editing and particle analysis is done with ImageJ (Schindelin et al., 2012). For the analysis, individual grain positions and tracks in a cartesian coordinate system are generated by the TrackMate plug-in (Tinevez et al., 2017). Particles are not spatially resolved. **In case of two overlapping particles, one track is cut but continued if the particle appears again.** A wrong assignment can be prevented by customizing parameters of the particle-linking processes. For our analysis, particle track length is not important due to the large amount of data averaging out details with most cases allowing determination with low errors on the percent level. The same is true for particle positions and closeness (see below) which is not sensitive to and does not require a detailed search for the best individual particle position algorithm. Velocities are determined from **short parts of these tracks.**

The center of rotation of the chamber is determined by viewing at the superposition of images of a grid placed inside the rotating chamber. With the known center of rotation and an **assumed rigid rotation of the gas**, the sedimentation velocity relative to the gas is deduced.

2.2 Coordinate System

Although a rotating system was examined, it is important to emphasize, that the coordinate system is neither rotating nor cylindrical, but Cartesian. The point of origin of the chosen coordinate system is in the center of rotation of the vacuum chamber; **rotation is at rate $\Omega = 2\pi f$ and rotation axis defined by the x -axis along the horizontal plane. The z -axis shows then in the opposing direction of gravity (see Fig. 2 for the definition of axes).** As we will see, the Ekman number of our rotating gas chamber, indicating the relative importance of rotation (Coriolis forces) in comparison to viscosity is weak,

$$\text{Ek} = \frac{\text{Ro}}{\text{Re}} \approx 0.025, \quad (1)$$

and in the absence of any perturbations but the particle feedback leading to a **rigid rotation of the gas** with

$$u_x = z\Omega; \quad u_z = -x\Omega; \quad u_y = 0 \quad (2)$$

The relevant forces in the experiment are gravity $F_g = mge_z$ and the drag force $F_d = -\frac{v-u}{\tau}$, thus individual particle motions are approximately given by

$$\dot{v}_x = -\frac{v_x - z\Omega}{\tau}, \quad (3)$$

$$\dot{v}_y = -\frac{v_y}{\tau}, \quad (4)$$

$$\dot{v}_z = -\frac{v_z + x\Omega}{\tau} + g. \quad (5)$$

Neither centrifugal nor Coriolis forces enter this system, as it is given in non-rotating coordinates. Corotation would not **help**, as then the vector of gravity would rotate as well. In general this leads to the **well-known** solution **$v_z - u_z = g\tau_f e^{-t/\tau_f} - g \cdot \tau_f$** . Regarding the short friction time of **$\tau_f = 7 \text{ ms}$** and the **rotation timescales of the experiment of about 1s** the term can be neglected. Thus in equilibrium, e.g. for short friction times (and we have **$\tau\Omega \ll 1$**), the particle motion is given by

$$v_x = -z\Omega; \quad v_z = (x + \frac{\tau g}{\Omega})\Omega; \quad v_y = 0, \quad (6)$$

which is rotation at rate Ω shifted by $dx = \frac{\tau g}{\Omega}$ from the rotation center of the gas. Therefore, in

y -direction only the terminal velocity of the particles (eq.12) is relevant. In x -direction the particles move along with the gas as again due to the small friction time the particles couple quickly. As a result, single unperturbed particles either levitate at an equilibrium point or are trapped in closed orbits around this point.

Centrifugal forces at the equilibrium point are zero. If going to corotating coordinate system around the equilibrium point, the centrifugal forces are orders of magnitude smaller than gravitational acceleration $\Omega^2 r \ll g_z$, see Section 3. The radial outward drift $v_r = \tau\Omega^2 r$ brings then also Coriolis forces as a second order correction with $f = 2\tau\Omega^3 r$, which is **even tinier than the centrifugal term. Nevertheless in the detailed numerical modeling we have these effects included, because we adopt the non-rotating frame.**

2.3 Experimental parameters

A summary of the most important parameters of the experiment is given in table 1. For this first study we used hollow glass spheres to get clouds of large non-sticky particles with low particle density for short gas-grain coupling times. Here, non-sticky refers to the fact that the grains are **sand size** and not supposed to stick together easily due to surface **forces** upon collisions as opposed to micrometer sized dust. An image of the particles is shown in fig. 3. The grains have an average di-

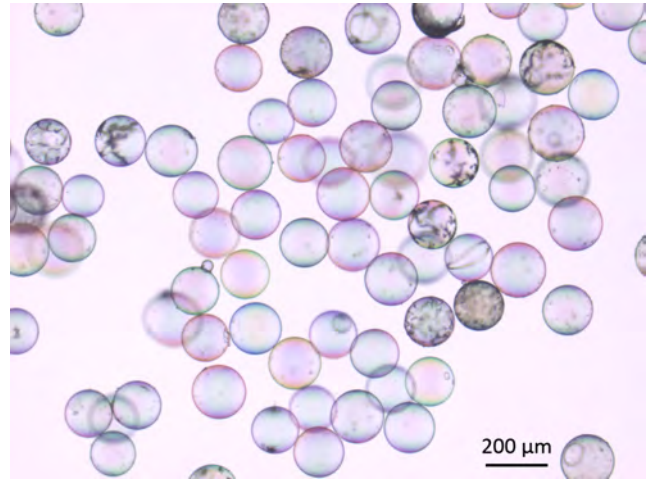


Fig. 3 Microscopic Image of the hollow glass spheres used. The beads are placed on a microscopic slide.

ameter of $165 \mu\text{m}$, **closer in size to sand than to dust**. However, we will stick to terms like dust to gas ratio here for the relation between particle mass and gas mass. For gas, we used **air**.

Table 1 Experimental parameters: Besides for the grain size, where the range is specified for all parameters deduced from this, only average values are given.

Parameter	Value
particle size	$165 \mu\text{m} \pm 15 \mu\text{m}$
particle density	60 kg/m^3
initial particle number	650
gas pressure	$950 \text{ Pa} \pm 100 \text{ Pa}$
initial dust-to-gas	0.15 ± 0.02
final dust-to-gas	0.07 ± 0.01
max. local dust-to-gas	1.4 ± 0.1
initial volume filling factor	3×10^{-5}
friction time	7 ms
Knudsen number	0.08
rotation frequency f	0.336 Hz
Stokes number	0.014
Re_{Setup} with $d = 22 \text{ cm}$	18.5

Particle size and particle density are specifications of the manufacturer. The size distribution was verified via microscopic images, but there are concerns regarding the particle density (see section 4.1).

The initial and final dust-to-gas-ratios are calculated using eq. 17 with an estimated volume of $V=31800 \text{ mm}^3$, which is derived from the area of all possible stable particle trajectories and an estimated depth of 5 mm corresponding to the thickness of the injected particle beam. The local dust-to-gas-ratio is calculated within a fraction of the measurement volume of $V=125 \text{ mm}^3$, again with 5 mm depth.

Considering the depth of view of the camera, the measurement volume increases by a factor of 10 and therefore the values of ϵ decreases by the same factor.

The friction time is calculated regarding the terminal velocity of undisturbed sedimenting particles to prevent errors resulting from uncertainties in particle density. Therefore, also the Stokes number isn't influenced by this.

Since particles move in an depth of 5 mm, one can give an error of 1% in all quantities where the particle position is important, namely velocities, friction time, Stokes number, Reynolds Number, local ϵ and Closeness.

2.4 Dust-to-Gas ratios

For the average dust-to-gas ratio ϵ , we take the particle mass over gas mass within the volume initially filled with particles. Due to slow drifts and due to collisions with the chamber walls, the particle density decreases with time. This is shown in fig. 4. In agreement with the estimates above, significant changes occur in 10 orbits, or 30 s. Details for clumps of different closeness are given below.

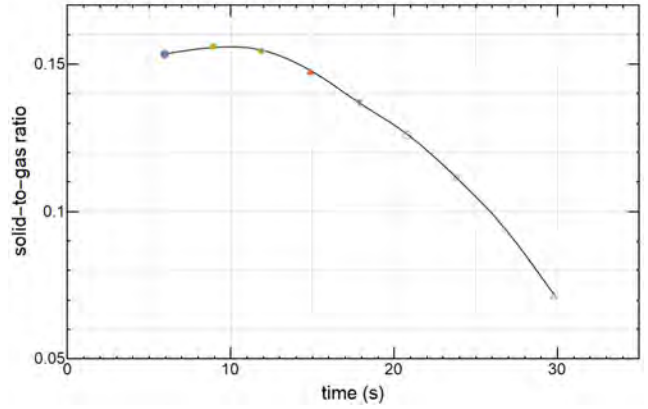


Fig. 4 Global dust-to-gas ratio over time. Dust density is calculated with respect to injected particle depth. The colour and shape of the data points correspond to the points in fig. 8

It has to be noted that these dust to gas ratios are calculated based on the average grain size, the observed number of grains and the 5 mm thickness of the injected particle beam. If the beam were to disperse along the cylinder axis over time, then the low densities at later times would be lower.

3 Grain-Gas Interaction

The motion of a single particle embedded in a gas is depending on the gas-grain coupling time or friction time τ_f .

τ_f is only well defined (constant) in flows where the drag force is proportional to gas speed. This is valid for small Reynolds numbers, which is the case here. In detail, the coupling time depends on the flow regime, which can be described by the Knudsen number Kn . The Knudsen number is the ratio between the mean free pathlength between the molecules λ and the particle radius r ,

$$Kn = \frac{\lambda}{r} \quad (7)$$

For small $Kn \ll 1$ the flow is continuous. For large $Kn \gg 1$ the flow is molecular. For molecular flow, the coupling time for a spherical particle of radius r is given as

$$\tau_{fE} = \frac{4 \rho_p r}{3 \rho_g v_g} \quad (8)$$

with ρ_g as gas density, ρ_p as particle density and v_g as thermal gas velocity. For small Kn , Stokes law applies and it is

$$\tau_{fS} = \frac{2r^2 \rho_p}{9\eta} \quad (9)$$

with the viscosity η . For $Kn \sim 1$ eq. 9 can be used, if a correction factor f_c is added.

$$\tau_f = \tau_{f_S} \cdot f_c. \quad (10)$$

Here, f_c is the Cunningham correction (Cunningham, 1910; Hutchins et al., 1995)

$$f_c = 1 + Kn(1.257 + 0.4e^{-0.55Kn}) \quad (11)$$

If a particle is dragged through a fluid with constant external force F_{ext} it will be accelerated until the drag compensates for this force. This leads to a constant velocity v_{rel} relative to the gas in equilibrium. In the case of gravity with gravitational acceleration g it is

$$v_{rel} = g \cdot \tau_f \quad (12)$$

However, if the gas motion changes on a timescale τ_{gas} comparable to the friction time, this simplification no longer holds. Therefore, an important quantity for describing the system is the Stokes number, which is the ratio between coupling time and typical time for gas motion variation.

$$St_0 = \frac{\tau_f}{\tau_{gas}}. \quad (13)$$

In turbulence, τ_{gas} usually describes the correlation time of the smallest turbulent eddies in the flow. **A different Stokes number** plays a major role in our experiments, where we take τ_{gas} to be the rotational timescale $\tau_{gas} = 1/(2\pi f) = 1/\Omega$ of the experiment chamber, as the gas follows this motion. Here, f is the rotation frequency and $St = \tau_f \cdot 2\pi f$.

This Stokes number, e.g., allows an estimate of the time that a particle can stay trapped in the rotating flow or the timescale on which the cloud gets thinner, limited by centrifugal losses as follows. The radial drift velocity resulting from the centrifugal acceleration from the rotating chamber is

$$v_r = \tau_f \Omega^2 r. \quad (14)$$

To first order, the time t_d needed to double this orbit is determined by $v_r t_d = r$. As t_d is given by the number of rotations N_d , and the rotation frequency by $t_d = N_d/f$, we can estimate the number of rotations N_d to double the orbits by (Klahr & Henning, 1997)

$$N_d = \frac{1}{2\pi St}. \quad (15)$$

With our chosen **$St = 0.014$** for the experimental setup (see below), typical changes e.g. of the dust to gas ratio occur in about 10 rounds or 30 s.

The Stokes number as referred to in the planet formation context $St_{Kepler} = \tau_f \Omega_{Kepler}$ has a different meaning. Here, one uses Ω_{Kepler} , the orbital frequency

of the disk. This Stokes number scales the radial drift rate of particles in the nebula to (Weidenschilling, 1977)

$$v_r \propto -2 \frac{St_{Kepler}}{1 + St_{Kepler}^2}, \quad (16)$$

indicating that a maximum of the radial inward drift occurs for $St_{Kepler} = 1$.

From work on streaming instabilities, significant growth rates are expected to start for $St_{Kepler} \geq 0.001 - St_{Kepler} \geq 0.01$ (Drazkowska & Dullemond, 2014; Bai & Stone, 2010a; Yang et al., 2017; Carrera et al., 2017), because drift between two components is essential for the onset of any Resonant Drag Instability.

In both cases, experiment and disk, a low Stokes number indicates that the mean motion of particles, being either radial drift toward the star, or sedimentation and centrifugal motion in the laboratory, can be described by a terminal velocity to first order (eq 12). Eq. 12 holds strictly speaking for small Stokes numbers St_0 , which should be given in our low Reynolds number ($Re = \frac{\rho_{gas} \cdot v \cdot d}{\eta} = 0.007$ for a single sphere) quasi laminar setup of the rotating gas in the experimental chamber. In other words the St_0 will initially be smaller than St , but this may change if the particles themselves drive additional gas velocities. A violation of Eq. 12 is then the route to further increase the local dust-to-gas ratio via turbulence (independent of whether we consider the solar nebula or a laboratory flow), which otherwise may be hard to achieve (Johansen & Klahr, 2005). Maximum concentration in a turbulent flow occurs for $St_0 = 1$ particles (Ormel & Cuzzi, 2007). While the linear streaming instability can indeed concentrate radially drifting particles in the solar nebula (Youdin & Goodman, 2005), **such a linear instability, so far, is not known for sedimenting spherical particles in laboratory. For non-spherical grains, an instability could be identified (Koch & Shaqfeh, 1989).**

The dust to gas ratio mentioned several times is another important parameter. For the global or average ratio, we define ϵ as ratio between average particle mass density and average gas density ρ_g .

$$\epsilon = \frac{\frac{N \cdot m_p}{V}}{\rho_g} = \frac{4}{3} \pi r^3 \frac{N \rho_p}{V \rho_g} \quad (17)$$

Here, ρ_p is still the bulk density of the individual grains (not average solid density), V is the total volume covered by particles, N is the total number of particles injected and m_p is the grain mass. The local motion of a particle will depend on other particles, as they back-react on the gas. Grains can be considered as "test" particles if $\epsilon \ll 1$. Based on a simple inertia argument, collective motion occurs at least if $\epsilon \geq 1$. It is one motivation of our work to study at what point exactly the

density dependence of particle motion sets in while ϵ is still well below 1.

In detail, the local particle (or "dust") density will differ from the average value and change the motion of local grains. During the study underlying this paper it became clear that local density is not enough as parameter. In hindsight, the argument would have been that for a high density clump it would be important how large this clump is. I.e., many particles at larger distances might have influence similar to that of a few particles in a closer neighborhood. This complicates the situation, as spatial regional limits are not well defined in a fluctuating density field. We therefore introduce as new parameter the closeness C_i of particle i , which accounts for both local number density of grains and distances between grains, as

$$C_i = \sum_{n=1}^N \frac{1}{r_n - r_i} \quad (18)$$

A graphical representation of the concept of closeness is seen in fig. 5. Note that here, r_i is the position of grain

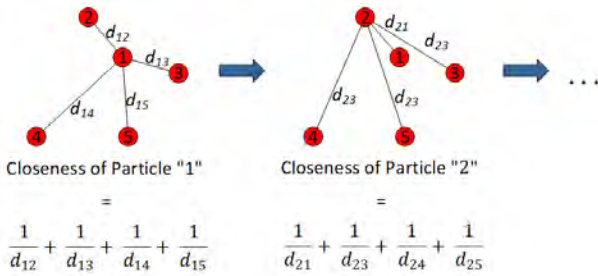


Fig. 5 On the definition of **closeness**

i , not its radius. Closeness or valued centrality is often used in the literature in graph theory as a measure of centrality in a network (Marchiori & Latora, 2000; Dekker, 2005). The $1/r_i$ -dependence in this definition is also known from the long-range hydrodynamic interactions of sedimenting spheres in Newtonian fluids under creeping flow conditions (e.g. Brady & Bossis (1988); Segre et al. (1997); János et al. (1997)). So for this first study we consider this definition of closeness as suitable parameter to quantify the influence of a region on an individual grain's motion.

We note that closeness might not be intuitive, so we caution the reader that closeness is constructed from distances and numbers of particles, and has a unit of $1/\text{m}$. For our global initial dust to gas ratio $\epsilon = 0.15$, assuming homogeneously distributed particles, the closeness would have a maximum in the center of the chamber, and we find $C = 16.7 / \text{mm}$, and a minimum toward the edge of the chamber of $C = 9.3 / \text{mm}$, while the

mean closeness would be $C = 13.9 / \text{mm}$. The fluctuations we find in the experiments of up to $C = 40 / \text{mm}$ are significant deviations from the mean value and already indicate a rather non-homogeneous cloud.

4 Grain Motion

4.1 Grain Motion at Low Particle Loading

Especially at low dust-to-gas ratios, the absolute gas motion coincides with the rigid rotation around the center with the set rotation frequency. For all particles we calculate a relative velocity by assuming the gas to be in such a circular motion and subtracting this absolute motion. Centrifugal parts are neglected. Grains in steady state sedimentation should move on circular orbits in the laboratory reference frame, with $v_{rel} = \tau_f g$ relative to the gas. Indeed this is the case. Fig. 6 shows the motion of individual particles. Due to the limited

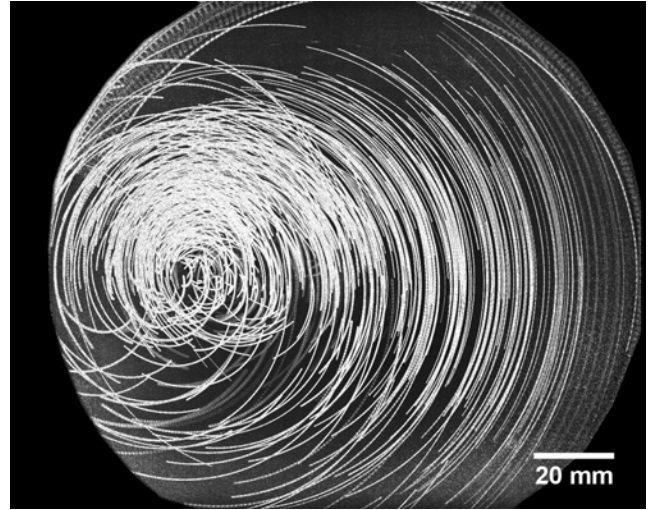


Fig. 6 Particle tracks as superposition for 1/4 of a rotation. The chamber rotates clockwise. Due to variations in sedimentation speeds studied, there is a range of equilibrium positions. Therefore, the circular tracks have different centers.

variation in particle size the point of stability, which is the center of the circles (not the center of the chamber), is similar for all particles. The calculated sedimentation velocity for an average particle is 50 mm/s , but this bears uncertainties e.g. in **bulk density**, which is not well constrained. We therefore determined the sedimentation velocity of a single grain by dropping individual grains in a gas of the same pressure used here and find a sedimentation velocity of 69 mm/s , roughly consistent with the calculated value. This value for a single grain fits well with observed sedimentation velocities of the rotating grains at low particle loading, with an average

of 68 mm/s (see fig. 8 below). The closeness in this case of lowest ϵ reaches up to 20 /mm but has no influence on the average sedimentation velocity.

Comparing the measured and calculated sedimentation velocity, a bulk density of approximately 75 kg/m³ would fit to the real terminal velocity rather than the manufacturer specification of 60 kg/m³. In this regard, the dust-to-gas ratios given in that paper are underestimated by a factor of roughly 25%.

4.2 Grain Motion at High Particle Loading

After injection, some particles always get lost, decreasing the overall number of grains. While the average dust-to-gas ratio ϵ only varies by about a factor of two between the beginning of the experiment (high ratio) and the end (low ratio), the variation in particle motion is much stronger. Fig. 7 shows a snapshot of the variations of local dust to gas ratios at early times, with values up to $\epsilon_{local} \geq 1.4$. Particles in regions with high

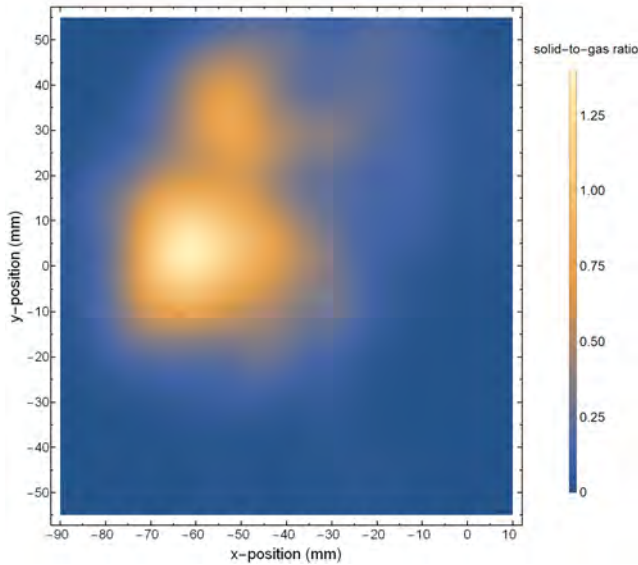


Fig. 7 Snapshot of local dust-to-gas ratio at early times (dense state) based on 2d projections.

closeness now sediment much faster than particles in less close regions, as seen in fig. 8 (lower data). This figure shows the sedimentation velocities and closenesses averaged over one full rotation each. This time sequence correlates to a change in the global ϵ (see e.g. fig. 4 which uses the same symbols). The solid to gas ratio decreases from about $\epsilon = 0.15$ at round 2 at 6 s (lower curve in fig. 8) to $\epsilon = 0.07$ at round 10 or 30 s (upper curve), as seen in fig. 4.

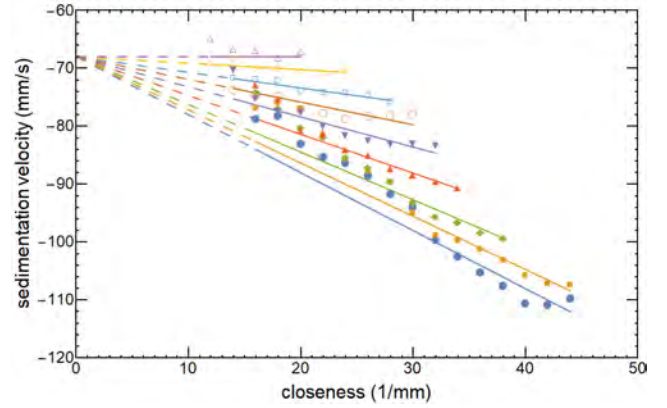


Fig. 8 Sedimentation velocity over closeness for individual rotations of the experiment chamber. The evolution with time goes from initially dense clouds (lowest curve, 2nd round) to less dense clouds (upmost curve, 10th round). Data are average values for typically a few 100 particles. Lines are linear fits to the data of each round.

As described above and visible in round 10 (fig. 8), for particles at later, less dense times, all particles sediment with the same speed, also at a closeness 20 mm⁻¹. In contrast, in the high loading case, the speed of particles with small closeness also increases with closeness. Obviously the system becomes sensitive to closeness and closeness variation only in the denser case.

As a first approximation, the dependence of the sedimentation speed on closeness can be described as linear or

$$v = v_0 - F_s \cdot C_i \quad (19)$$

This slope F_s corresponds to the lines in fig. 8. Note that v and v_0 are negative in our notation of sedimentation. The sensitivity factor F_s is not constant over time. It increases with the average closeness or dust to gas ratio of the system, as shown in fig. 9. Therefore, in total the sedimentation velocity can be expressed as

$$v = v_0 + \alpha \cdot (\epsilon - \epsilon_{crit}) \cdot C \quad (20)$$

if ϵ is larger than a critical ϵ_{crit} .

If the total cloud is sensitive (large ϵ), and if a region of high closeness forms or approaches a particle, this particle can join this region of high closeness and sediment faster. This is in contrast to thinner clouds where all particles essentially move independently.

This does not imply an instability with steadily growing particle number as grains can also drop out of high closeness regions. Trajectories of such particles are shown in fig. 10.

Fig. 11 shows the evolution of closeness attributed to a single particle over time and the corresponding sedimentation speed. Closeness is the main parameter describing single particle trajectories, though other not

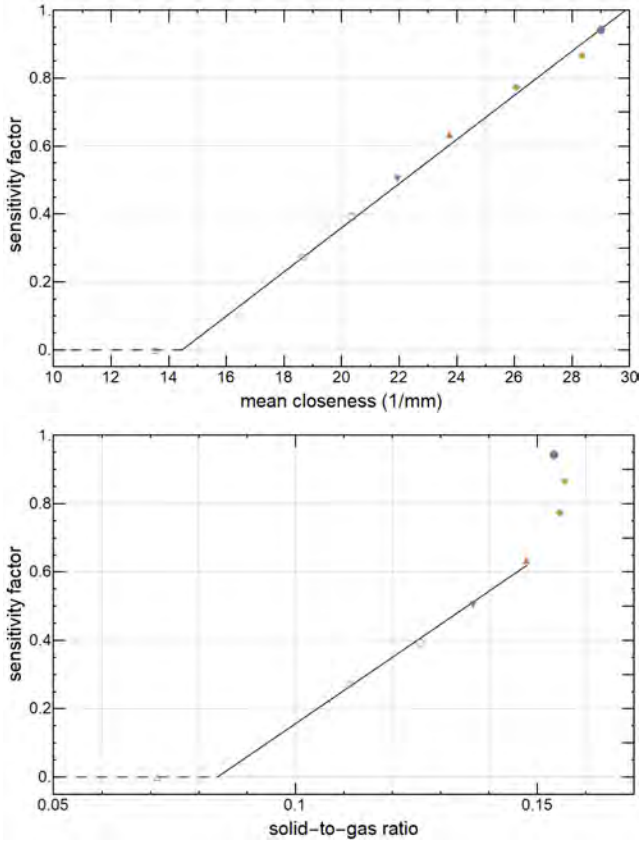


Fig. 9 Sensitivity factor dependence on average closeness (top) and dust-to-gas ratio (bottom)

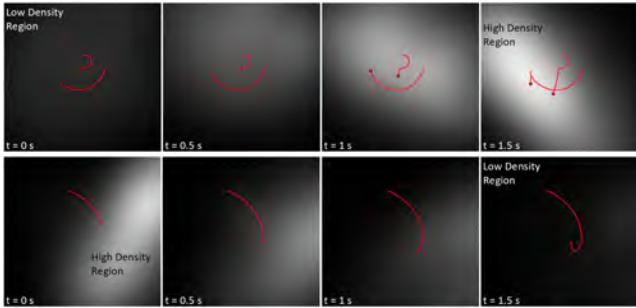


Fig. 10 Top: Particles entering a region of high closeness getting entrained; Bottom: Particle leaving a high closeness region staying behind. Dark background colour corresponds to low particle-density region and light background colour to high-particle-density region. The trajectories are coloured red for better recognition. The images originate from real measurements and show a 20x20 mm image section.

yet examined influences lead to small deviations in sedimentation velocity from an average behavior.

At late times all particles on average sediment like individual grains with calculated sedimentation velocity. However, the speeds still vary due to variations in particle size. Typical velocity distributions for the low density case are seen in fig. 12 (right distribution). At earlier times (time 6 s, round 2) variations due to an

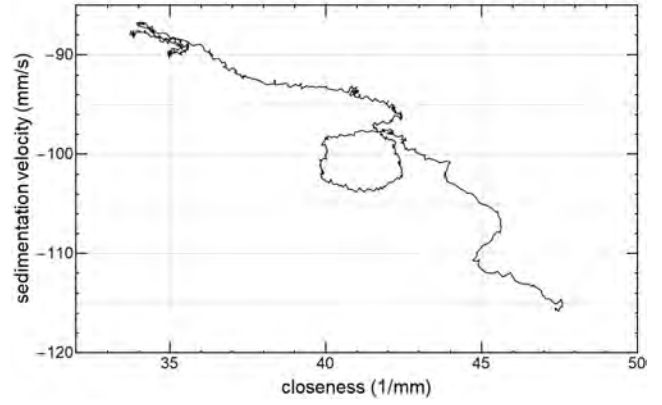


Fig. 11 Example of an individual particle in a dense cloud in a closeness-velocity diagram.

increased sensitivity are added, and the variations are much larger as seen in fig. 12 (left distribution). Note that lower values due to the negative values are higher absolute sedimentation velocities.

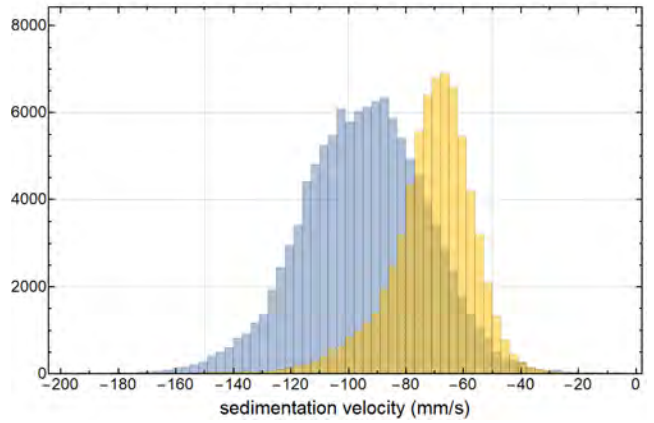


Fig. 12 Sedimentation speed for low particle loading (right distribution) and high particle loading (left distribution)

Fig. 13 shows the closeness distribution changing from late to early. As can be seen, the initial closeness distribution has a wing at the high value side which it loses first. In general, particle regions with high closeness are preferentially lost, leading to an inclined distribution, with steeper drop off to higher values. This is due to the fact that particles sedimenting faster have a smaller stable region to rotate within the experiment and are more easily lost to collisions with the wall.

Some of this is summarized in fig. 14. It shows that the relative width in velocity essentially stays constant but the initial fluctuations at high dust-to-gas ratio are much broader. The relative width at later times (lower dust-to-gas ratio) is only somewhat wider than the size distribution of about 20% full width. Otherwise, this is

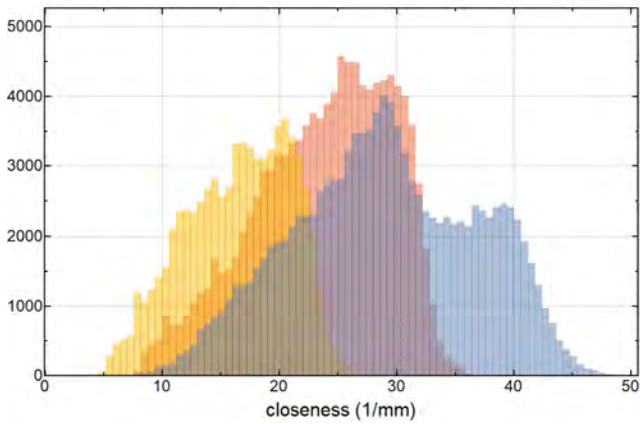


Fig. 13 Evolution of the closeness distribution for 3 different times from right distribution (early) to left distribution (late)

similar to findings in other sedimentation experiments. E.g. Guazzelli & Hinch (2011) find an increase of the relative width with filling factor (proportional to dust-to-gas ratio). However, the dependence they find is very weak at the low filling factors relevant for our experiment. This implies that in a region of higher closeness, where the average behavior changes and the sedimentation velocities increase also the variation in speeds increases in the same manner. **Sedimentation of individual grains in a pack of grains obviously remains linear to particle size in such regions.** This is valid up to a dust-to-gas ratio of 0.15 in our case. If this is a real transition remains to be seen in experiments approaching higher dust-to-gas ratios from the lower end.

5 Discussion

In this work, we used the laboratory setup of a rotating experiment to study particle clouds at varying, but in general high, dust-to-gas ratios for a longer time in spite of sedimentation under Earth's gravity. This allows an analysis of the particle motion in the presence of other particles for different conditions. The basic parameter that is measured is the sedimentation velocity of all individual particles and their distances (in 2d). Variations in the *local* dust-to-gas ratio are important, but this value is not sufficient to describe the motion of a local particle cloud as it neglects the influence of neighboring regions on the particle motion. We therefore defined the closeness as another parameter for each individual particle which depends on all particles and their distances to the particle considered.

We can separate two regimes of particle motion. For dust-to-gas ratios below $\epsilon = 0.08$ particles behave like test particles embedded in a gas. That means that they essentially do not feel the presence of the other par-

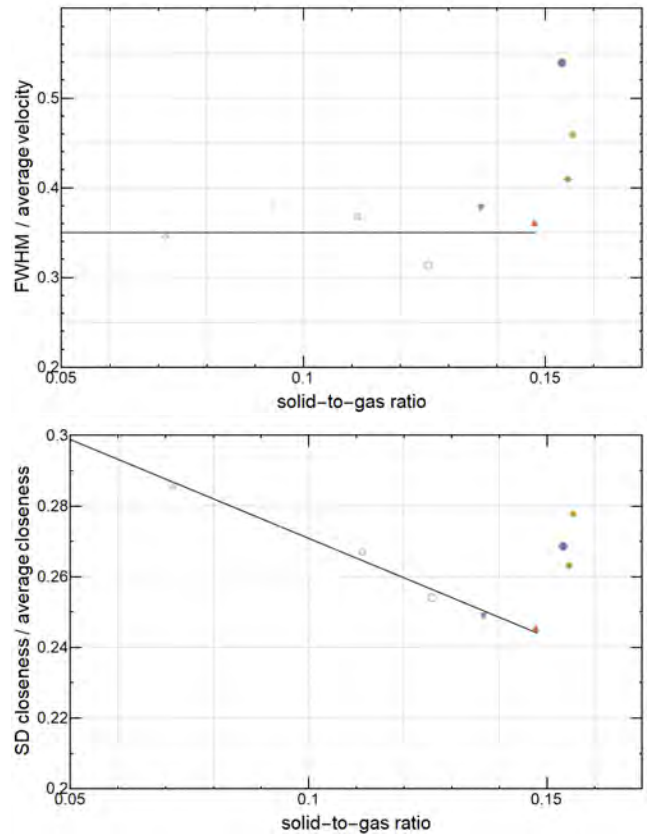


Fig. 14 relative velocity width / average velocity and relative closeness width / average closeness over dust-to-gas ratio

ticles, or in other words they sediment like individual particles would sediment. There is no collective effect. This even holds for regions of closeness up to 20 mm^{-1} . As closeness might not be an intuitive quantity, it might be argued that the largest closeness might still be representative of a dilute cloud corresponding to test particle behaviour. However, this argument does not hold for denser clouds.

For dust-to-gas ratios above 0.08 all particle motion does depend on closeness. So for high dust loading, particles of closeness well below 20 mm^{-1} also have much higher sedimentation speeds than individual test particle grains should have, and it varies with the closeness of a grain. To first order, the speed is now also linear in closeness for small values of closeness, and the *inclination* of this linear dependence is sensitive to the dust-to-gas ratio or average closeness.

We therefore defined the absolute of the *inclination* as the sensitivity factor. The sensitivity factor becomes zero at a dust-to-gas ratio below $\epsilon \leq 0.08$, which quantifies the separation of the two regimes of test particle behavior for lower values and collective motion above.

The influence of the closeness on the sedimentation velocity is reminiscent of similar findings on sediment-

ing clouds in the Stokes Regime. There, all particles perturb their surrounding gas velocity inversely proportional to the distance of the gas, leading to a correction term in the sedimentation velocity on the order of $O(1/r)$ (Guazzelli, 2006). However, in Guazzelli (2006), a well confined sedimenting cloud forms a torus, and finally breaks up. We did not observe anything like this and **consider the situation to be different.**

Nevertheless, as a plausibility check we might consider the following simplified picture. If the global dust to gas ratio is sufficiently large the total cloud is sufficiently *opaque* for the gas, and can be considered as a single particle in the Stokes regime. In contrast, at later times with a low average dust-to-gas ratio, the cloud becomes *geometrically thin* and gas streams through it unhindered, and the cloud can no longer act as one big Stokes particle. Therefore, in the first case (Stokes-Regime) the closeness plays a role, where as in the second case (Knudsen regime) no such effect can be observed.

As a criterion on when the cloud is "opaque" for the gas, one can estimate the velocity change δu the gas experiences as it streams through a particle cloud of dimension a at a given dust to gas ratio ϵ .

$$u = -\epsilon \frac{v_0}{\tau_f} t_a. \quad (21)$$

With $t_a = a/v_0$ being the crossing time for gas through the clump, we can claim that significant opaqueness is given when $u = v_0$ and thus:

$$\epsilon_c = \frac{v_0 \tau_f}{a}. \quad (22)$$

Plugging in a cloud size from Fig. (7) with about $a = 40$ mm, $v_0 = 70$ mm/s and $\tau_f = 7 \cdot 10^{-3}$ s results in a critical density of $\epsilon_c = 0.01$, and we see that the actual ϵ values indicate easily that this clump can not be penetrated by the gas. At late times when the clumps are no longer as big as initially, say for instance $a = 5$ mm, the critical value for dust-to-gas would be $\epsilon_c = 0.1$, which is on the order of the transition in Fig. (9), when collective effects involving closeness are no longer observable. This is only a first qualitative reasoning. Certainly, there is e.g. a limit in increasing the size of a cloud at low dust to gas ratio to trigger collective behavior. Otherwise, any part of a protoplanetary disk would easily become collective.

In detail, at times of high mass loading in the experiments, individual particles in low closeness regions with small sedimentation velocities can change their motion by entering regions of high closeness passing by, speeding them up. However, they can also drop out of warp again into a region of lower closeness, thus slowing down.

We see fluctuations but do not see any concentration effect yet, leading to a continuous local increase of particles. Whether sedimentation induced gas flow and the associated turbulence can lead to local particle concentrations in a non-linear fashion is still an open question.

With the current design, the experiment is biased to losing sub-clouds of high closeness or particles with high sedimentation speeds. The stability point of fast particles is closer to the experiment wall and therefore the stability region is much smaller. Such regions are therefore preferentially lost due to collisions with the walls. This is also visible in the evolution of the closeness distribution, where the large values decrease more strongly than the small ones, leading to non-symmetric distribution with a small slope rising but a steep slope falling off toward larger closeness. In a way, the system cleans itself of very "close" or "unstable" regions. On the other side, the difference in centrifugal motion responsible in some way mimics streaming, as denser cloudlets move outward further and can collect individual grains.

The sensitivity factor dependence indicates that the average closeness might be better suited as a description for the dense regime than the average dust-to-gas ratio. At least the sensitivity factor is linear for all values of average closeness, while there is a deviation from linearity for the highest dust-to-gas ratio.

As far as sedimentation velocity goes, the variation (width) is linear in the absolute value. However, the closeness gets more pronounced at higher dust-to-gas ratios, but currently we would not give this a fundamental interpretation in view of the experimental constraints on cloud stabilities.

Boiling this down, the essence of this work is the finding of increasing sensitivity with increasing dust-to-gas ratio. For dilute systems, a local increase in particle density – or better, in closeness – has little effect. At high particle loading, small changes in particle density lead to large changes in the sedimentation velocity of that region, more so the denser the region.

This implies that some self-amplification of the fluctuations in ϵ could only work where denser regions move faster, pick up grains in slower, less dense regions, and move even faster. So far we are only approaching this state, **as these regions are unstable in the experiment and grains are lost to the walls.** It is a strong indication, though, that some sedimentation or also streaming instabilities, e.g. with centrifugal motion, might occur in laboratory experiments.

6 Summary

To sum this up, for a given experiment we can describe the absolute value of the sedimentation velocity of a particle as

$$v = v_0 \quad \text{for} \quad \epsilon < \epsilon_{crit} = 0.08 \quad (23)$$

$$v = v_0 + \alpha \cdot (\epsilon - \epsilon_{crit}) \cdot C \quad \text{for} \quad \epsilon \geq \epsilon_{crit} = 0.08. \quad (24)$$

The value of α is about 10.

This might be compared to the simple assumption of a single particle clump of size r_c sedimenting in an otherwise undisturbed gas.

$$v = v_0 + \beta \cdot (\epsilon - 0) \cdot r_c^2 \quad (25)$$

There are two principle differences. First, we do have a minimum solid to gas ratio, ϵ_{crit} , for which collective motion gets important. Second, we traded the clump radius, r_c , for the closeness, C , as we do not have a well defined clump size, and closeness accounts for the local particle density as well as the distance between grains.

7 Caveats and Future Work

There are limits in this work which might be improved in the future. Observations are only two dimensional and the particle distribution along the rotation axis is unknown. So absolute dust-to-gas ratios might systematically be estimated to be too high. This can be improved with an additional camera and viewing angle.

Even after much testing, this work is essentially only based on the analysis of a single experiment (except the examples of particles entering and dropping out of a dense region), as we had to develop an appropriate way of analyzing dense many particle systems, and to see where this might be leading. Certainly, the database has to be extended, but we consider our work here as important milestone.

There might be interesting physics in the dense (high closeness) regions that is lost early on. It might be that it is exactly the regions of high closeness early on, which are lost due to instability in our experiment, that correspond to unstable regions in the sense of a sedimentation instability. This is only a speculation at this point, though, as it might be due to the initial conditions and did not evolve into this state on its own. Dense regions might be kept longer if the experiment Stokes number is decreased, decreasing centrifugal losses. A decrease is possible but either requires slower rotation speeds, higher gas pressure, or smaller particles. The experimental capabilities still have to be explored.

Also, future experiments with low density clouds which are compressed or enhanced afterwards by some means will provide deeper insight.

We started with the premise that at low particle loading, particles move through a gas in rigid rotation, defining a relative sedimentation velocity. The gas motion will change in a more complex way in the case of high mass loadings. After all, it is the gas that mediates the coupling between grains. The calculated sedimentation velocities are therefore still a well defined construction, but at some point might loose the simple interpretation of relative velocity between grains and gas.

To make the laboratory findings and laboratory extension more applicable to protoplanetary disks, we intend to numerically simulate the experiment, gas and particles.

The fact that the individual particles are in the Knudsen regime, whereas the clumps are in the Stokes regime, is the typical case for a protoplanetary disk, thus to study this transition in experimental setups and accompanying numerical simulations will help us to also produce more reliable predictions for the occurrence of the streaming instability.

Electrostatic charging of the grains might have an influence on the cloud evolution. We cannot exclude that grains are charged. In fact, Yoshimatsu et al. (2017) used similar hollow spheres and showed that particles charge up after several seconds of intense vibration. However, they only observed this under microgravity. Also Jungmann et al. (2018) showed that the effects of high charges on grains only got important during collisions and it is certainly important during sticking (Lee et al., 2015). As our particles are considered to be collisionless and as we did not observe the formation of aggregates, we do not consider charging to be important here.

8 Conclusion

We define a Stokes number in the experiment with respect to the experiment rotation timescale which turns out to be 0.014. This is a different Stokes number than the one defined in disks around young stars to define the triggering of the streaming instabilities for an estimated critical dust to gas ratio of $\epsilon = 0.027$ (Yang et al., 2017). Local concentrations of particles in both situations require local turbulent Stokes Numbers of order unity. This means that particles get concentrated when their friction time is on the order of the local turbulent correlation time. This is the case for the so far only numerically studied streaming instability in disks around

young stars. Whether the sedimentation process studied in our experiments will also lead to velocity fluctuations and correlation times on the order of the friction time still has to be studied.

We see no collective behavior for low dust-to-gas ratios up to $\epsilon = 0.08$, which we interpret as a threshold for the gas in the Knudsen regime to recognize a collection of particles as obstacle to the flow.

However, above this value (being well in the Stokes regime for the clumps), all dust motion is increasingly sensitive to small disturbances of the particle's closeness which may or may not lead to unstable situations.

Overall, our laboratory experiments are but a first study. Nevertheless, this is the first experimental study of the underlying common ground physics of sedimentation and streaming instabilities at the transition from Knudsen to Stokes regime.

The results indicate that there is potential for future improvements, but we clearly approach collective behaviors. Further experiments will hopefully lead us to well confirmed pictures of particle concentration and planetesimal formation by self gravity and streaming instability.

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