



HAL
open science

An instrument for studying granular media in low-gravity environment

S Aumaître, R P Behringer, A Cazaubiel, E. Clément, Jérôme Crassous, D J Durian, Eric Falcon, S. Fauve, D Fischer, A Garcimartín, et al.

► **To cite this version:**

S Aumaître, R P Behringer, A Cazaubiel, E. Clément, Jérôme Crassous, et al.. An instrument for studying granular media in low-gravity environment. *Review of Scientific Instruments*, 2018, 89 (7), pp.075103. 10.1063/1.5034061 . hal-01802985

HAL Id: hal-01802985

<https://hal.science/hal-01802985>

Submitted on 30 May 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

An instrument for studying granular media in low-gravity environment

S. Aumaître,^{1,2} R. P. Behringer,³ A. Cazaubiel,⁴ E. Clément,⁵ J. Crassous,⁶ D. J. Durian,⁷ E. Falcon,^{4, a)} S. Fauve,⁸ D. Fischer,⁹ A. Garcimartín,¹⁰ Y. Garrabos,¹¹ M. Hou,¹² X. Jia,¹³ C. Lecoutre,¹¹ S. Luding,¹⁴ D. Maza,¹⁰ M. Noirhomme,¹⁵ E. Opsomer,^{15, b)} F. Palencia,¹¹ T. Pöschel,¹⁶ J. Schockmel,¹⁵ M. Sperl,¹⁷ R. Stannarius,⁹ N. Vandewalle,^{15, c)} and P. Yu¹⁴

¹⁾ SPEC, DSM, CEA-Saclay, CNRS URA 2464, F-91191 Gif-sur-Yvette, France

²⁾ Laboratoire de Physique, ENS Lyon, UMR-CNRS 5672, F-69007 Lyon, France

³⁾ Department of Physics, Duke University, Durham, NC 27708-0305, USA

⁴⁾ Université Paris Diderot, SPC, MSC, UMR 7057 CNRS, F-75013 Paris, France

⁵⁾ PMMH, ESPCI, UMR 7636 CNRS, F-75005 Paris, France

⁶⁾ Université Rennes 1, IPR, UMR 6251 CNRS, F-35042 Rennes, France

⁷⁾ University of Pennsylvania, Philadelphia PA 19104-6396, USA

⁸⁾ École Normale Supérieure, LPS, CNRS, UMR 8550, F-75005, Paris, France

⁹⁾ IEP, Otto von Guericke Universität, D-39106 Magdeburg, Germany

¹⁰⁾ DFMA, Universidad de Navarra, E-31080 Pamplona, Spain

¹¹⁾ CNRS, ICMCB, Université de Bordeaux, UMR 5026, F-33600 Pessac, France

¹²⁾ Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

¹³⁾ Institut Langevin, ESPCI Paris, PSL, CNRS, F-75005 Paris, France

¹⁴⁾ MSM, University of Twente, 7500 AE Enschede, The Netherlands

¹⁵⁾ GRASP, Institute of Physics B5a, University of Liège, B-4000 Liège, Belgium

¹⁶⁾ Friedrich-Alexander Universität, IMS, D-91052 Erlangen, Germany

¹⁷⁾ Institut für Materialphysik im Weltraum, DLR, D-51170 Köln, Germany

A new experimental facility has been designed and constructed to study driven granular media in a low-gravity environment. This versatile instrument, fully automatized, with a modular design based on several interchangeable experimental cells, allows to investigate research topics ranging from dilute to dense regimes of granular media such as granular gas, segregation, convection, sound propagation, jamming and rheology - all without the disturbance by gravitational stresses active on Earth. Here, we present the main parameters, protocols and performance characteristics of the instrument. The current scientific objectives are then briefly described and, as a proof of concept, some first selected results obtained in low gravity during parabolic flight campaigns are presented.

I. INTRODUCTION

Granular systems belong to a particular class of materials since grains may exhibit solid, fluid or gaseous behaviors. Although nearly 80% of the products used in industry are powders and grains, many fundamental questions concerning their rheology and their dynamics are still unsolved¹. Space exploration (such as regolith on asteroid surfaces, powder propellants of rockets, or planetary rings dynamics) and space exploitation (such as asteroid mining) will also face major challenges concerning the handling of granular materials in low-gravity environments²⁻⁴. For example, nobody knows how to perform a simple operation like sieving in space, whereas several month efforts failed to free NASA's Mars Exploration Rover Spirit from a Martian sand trap in 2010. Therefore, it is of primary interest to better understand the flow and the dynamics of granular media in low-gravity conditions.

On Earth, when granular matter is subjected to vibrations, liquid-like behavior occurs such as convective

flow⁵ or surface waves⁶. For strong enough forcing, gas-like behavior, with particular modes of momentum and energy transport⁷, arises where particles move erratically in response to the vibrations and the dissipative nature of collisions. When the density of particles increases within such a granular gas, the formation of a dense cluster of particles is observed due to inelastic collisions⁸⁻¹⁰. This cluster formation constitutes one of the most astonishing properties of granular matter under vibrations. When the forcing is stopped, numerical simulations have shown the formation of density gradients during the cooling (instability of the homogeneous cooling state)¹¹ as well as inelastic collapse (particles undergoing an infinite number of collisions in finite time)¹². However, several phenomena occurring on Earth (such as sedimentation, convection, and confinement pressure due to the weight of grains) disappear in low gravity, leading, thus, to strongly different behavior for granular matter.

Generally, ground based experiments are perturbed by anisotropy induced by gravity and by the friction force which acts on all the particles and which is far from being negligible. Low-gravity environment is, thus, needed for dilute regimes of vibrated granular medium because it is the only way to achieve an experimental situation in which inelastic collisions are the only interaction mechanism. For dense regimes, low-gravity environment is also needed to better understand the rheology¹³, sound

^{a)}Electronic mail: eric.falcon@univ-paris-diderot.fr

^{b)}Electronic mail: eric.opsomer@uliege.be

^{c)}Electronic mail: nvandewalle@uliege.be

propagation¹⁴ and jamming transition¹⁵ of dense granular media without confinement pressure of grains due to their own weight.

In order to address fundamental questions and potential applications regarding grains in a low-gravity environment, the European Space Agency (ESA) created in 2011 a Topical Team¹⁶ on the subject. Its objective is to perform unique measurements on granular gas, convection, segregation, sound propagation and jamming in granular materials subjected to vibrations without the symmetry breaking influence of gravity. In collaboration with DTM TechnologiesTM (Modena, Italy), the Topical Team designed the VIP-Gran-PF instrument (short for Vibration-Induced Phenomena in Granular Matter in Parabolic Flights) whose modular design allows to investigate both dilute and dense granular regimes.

This paper is organized as follows. Section II describes the experimental instrument and its performance. Section III presents the current scientific objectives, and, as a proof of concept, some selected results obtained with this facility during four ESA parabolic flight campaigns (PFC) onboard a modified Airbus A310 Zero-G aircraft. Finally, we draw our conclusions and perspectives in Section IV.

II. INSTRUMENT DESCRIPTION AND PERFORMANCE

The setup of the VIP-Gran instrument is displayed in Fig. 1. The basic principle of the experiment consists of a closed cell containing particles in which two opposite walls of the cell are pistons vibrating either in-phase or out-of-phase motions. Control parameters are the number of particles, the cell length (volume), the amplitude and the frequency of vibrations. Different interchangeable cells can be used depending on the scientific objective. Accelerometers are screwed in the shaft of each vibrating piston. Impact sensors are also implemented to measure the collision statistics of particles impacting on the pistons. Two cameras allow quantitative measurements including particle tracking in dilute regimes and correlations between particle displacements.

We describe below in detail the five major components of the setup: (A) Interchangeable experimental cells to be filled with granular material. (B) A bead feeder, that allows to add particles into the cells during the experiment. (C) The driving mechanism that allows the energy injection, the control of the volume and the confining pressure. (D) The accelerometers and impact sensors. (E) Two high resolution speed cameras to capture relevant data during the experiments and the illuminations.

A. Experimental cells

An experimental cell is a closed cuboidal container of $60 \times 30 \times h$ mm³, that can be filled by granular ma-

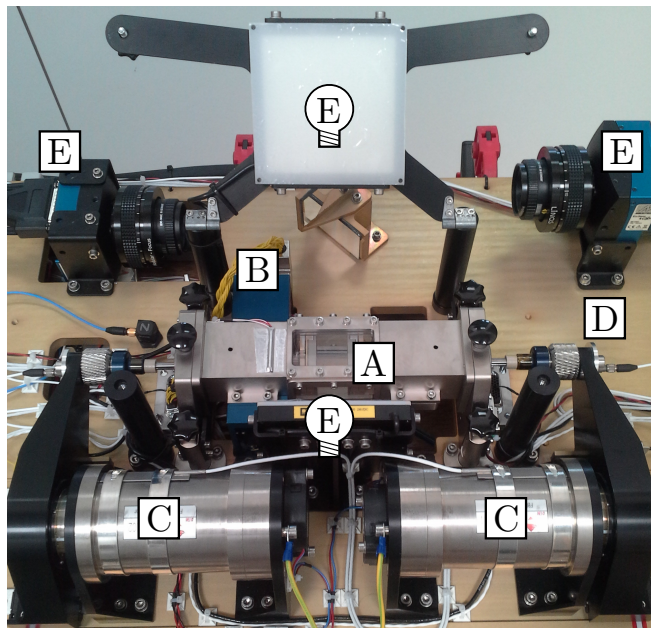
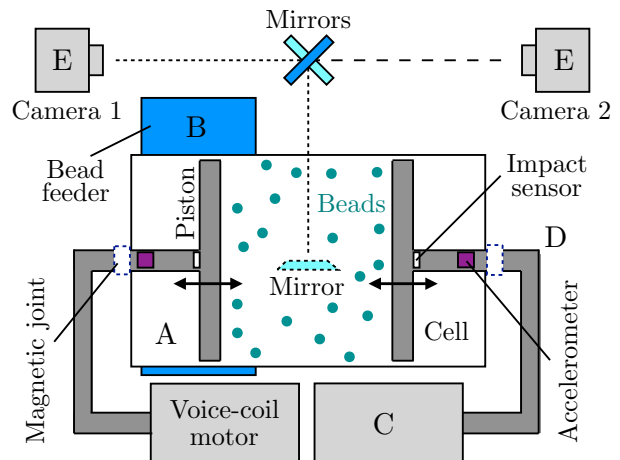


FIG. 1. Letters A, B, C, D and E refer to the main text. Top: Sketch (top view) of the VIP-Gran instrument. Two opposite walls, driven by voice coil motors, inject mechanical energy into the experimental cell containing a granular medium. Two cameras track grains or visualize the system from the bottom and from the side. Accelerometers and impact sensors are mounted on the shafts of the pistons to, respectively, control the energy injection in the system, and to measure the collision statistics of the granular medium with the pistons. Bottom: Picture of the instrument built by DTM TechnologiesTM for parabolic flight experiments.

terial (spherical and/or aspherical particles). The top, bottom and lateral sides of the cells are made of transparent Polycarbonate, 8 mm in thickness. The two opposite walls of the cell are connected magnetically to linear voice-coil motors, and act as pistons. The average distance, L , between the pistons can be adjusted in order to control the accessible volume of the system. Initially, a three-dimensional (3D) container ($h = 30$ mm) and a

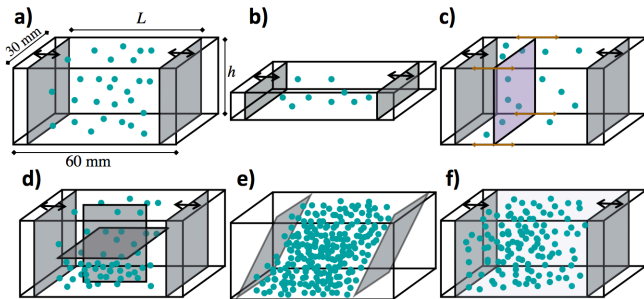


FIG. 2. Sketches of the experimental cells used in VIP-GranPF. Parameter L is tunable thanks to the two mobile gray walls that act as pistons. The height h is 30 mm for 3D cells, and 5 mm in the case of the quasi 2D cells. (a) 3D cell (b) quasi-2D cell, (c) 3D cell with a free moving wall, (d) 3D partitioned cell, (e) 3D shear cell, and (f) 3D wet cell. Cells can easily be exchanged thanks to a magnetic joint connection with the kinematic chain (see Fig. 1)

quasi two-dimensional (2D) container ($h = 5$ mm) were developed. A sketch describing these cells is given in Figs. 2a-b. Different modifications can be applied to the cells in order to conduct particular experiments. For instance, placing additional walls within the container, as in Figs. 2c-d, to create compartments can lead to trapping. Changing the curvature, or the roughness, of the pistons as in Figs. 2e-f can modify the energy injection into the system. Different physical phenomena and properties can be then investigated in low gravity within specific interchangeable cells: out-of equilibrium stationary states of diluted granular medium in cells (a) and (b), handling of grains in cells (c) and (d), rheology in cell (e) or sound propagation in granular media under weak applied confinement in a modified cell (a), as well as behaviors of rheology of wet grains in a sealed cell (f). Some cells like the modified (a), (e) and (f) being under development, we limit the discussion herein below to the use of the 3D cell (a) and the quasi 2D one (b).

B. Bead feeder

The experimental cells described in Sect. II A can be filled by spherical particles of different materials (bronze, steel, aluminium, glass, polyamide...) and different diameters, see Table I. Moreover, cylindrical steel rods were also tested. Granular matter can either be placed directly into the cells before the experiment or injected into them during the experimental runs using the bead feeder (see Fig. 3). The barrel of the bead feeder is divided into eight chambers each able to contain either 1000 small (1 mm) or 250 large (2 mm) spherical particles. Thanks to a motorized linear rail slide system, each chamber can be positioned in front of the entry hole of the experimental cell. A piston then injects the particles. Note that the bead feeder does not allow to extract grain which

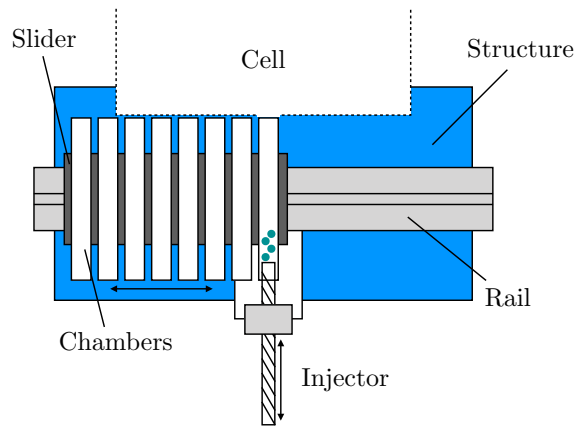


FIG. 3. Sketch of the bead feeder located below the cell. This device is used for the controlled injection of additional granular material into an experimental cell. It corresponds to letter B in Fig. 1.

means that, to start over again with new initial filling conditions, the cell has to be exchanged.

C. Driving mechanism

Two opposite walls of the cell are vibrating pistons (see Fig. 1). They are moved by two linear voice-coil motors driven by a selected vibration stimulus (sine, single-pulse, quasi-static ramp, ...). The forcing amplitude, A , of the piston is in the range $[0.2, 25]$ mm (peak-to-peak) and its forcing frequency, f , in the range $[1, 50]$ Hz. Note that the piston acceleration is limited to $5g$ (g being the acceleration of Earth gravity), meaning that some A, f combinations are not possible. For sine vibrations, pistons can oscillate either in phase or out-of-phase. Both pistons are controlled in displacement with an accuracy of $10 \mu\text{m}$ at an acquisition rate of 1000 Hz. Since the vibrating walls of each cell are connected to the linear motors via magnetic joints mounted on both shafts (see Fig. 1), the cells can be changed on the instrument. A cooling fan is positioned on the back of each motor to keep temperature constant.

D. Sensors and acquisition

Several sensors are installed in the instrument: accelerometers, impact sensors, linear positioning sensors, and temperature sensors. The two mono-axial accelerometers are screwed into the shaft of each vibrating piston to measure the piston's accelerations (8 kHz sampling frequency). One triaxial accelerometer is fixed on the breadboard, far away from the cell, in order to measure the ambient acceleration in response to the aircraft motions (1 kHz sampling rate). For 3D cells, the impact sensors are rectangular-shaped piezoelectric films mounted

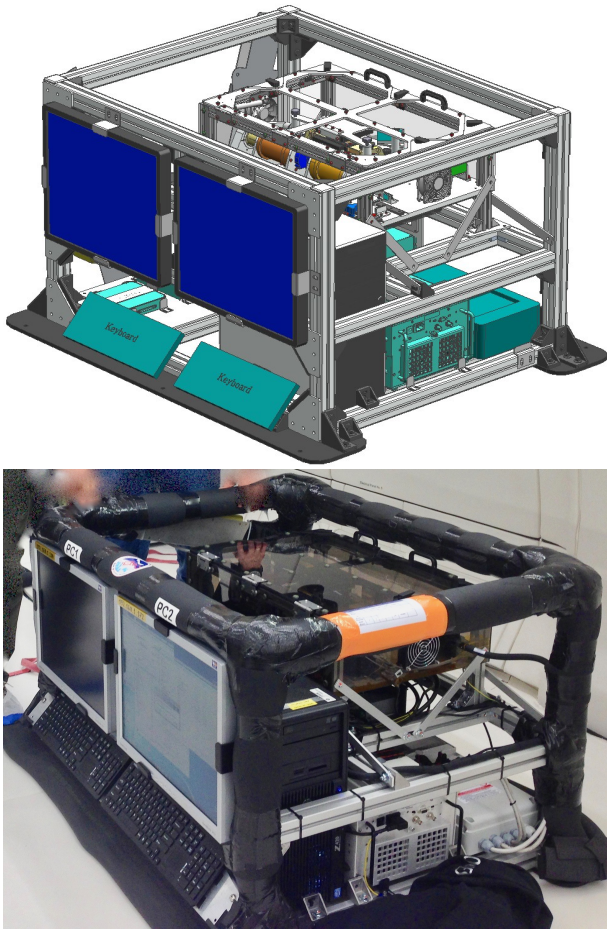


FIG. 4. Top: Drawing of the instrument rack by DTM TechnologiesTM. Bottom: Picture of the rack onboard the aircraft.

behind each vibrating piston, their axis being collinear with the vibration axis. Thanks to a 2 MHz sampling rate, each sensor is able to resolve the collision of a bead impacting on the piston wall. Such contact lasts a few microseconds since the typical velocity of beads is of the order of few m/s at most. The two linear sensors for controlling the piston displacements are acquired at 3 MHz sampling rate. Four temperature sensors are used to detect, at a 1 Hz sampling rate, any abnormal overheating of the experiment cell, of each linear motors, and of the ambient air, to be able to promptly switch off the motors in order to cool them down. The onboard workstation, the data acquisition system (interfaced by National Instruments cards) and electronics thus enable, for each parabola, high-frequency acquisitions of both video-images and sensor signals as well as programming the required experiment profiles (piston frequency and amplitude, oscillation type). The time-tagging of acceleration data and impact force sensor data, is synchronized with the image acquisition and the piston displacement (with a precision of 10^{-6} s.)

E. Video cameras and illuminations

The instrument enables the observation of the experiment by means of two high-speed cameras of frame 1000 fps with a resolution of 1024×1024 pixels (Mikrotron EoSens 4CXP). The camera frame rate can be chosen down to 1 fps, if low-speed acquisition is needed notably for experiments regarding dense regime. Observations are made in two perpendicular directions, themselves perpendicular to the vibration axis. This corresponds to a bottom and a side-view observation in Fig. 1. The depth of field is selectable, whereas the field of view covers the full cell during vibrations. At full rate and resolution, 1.4 TBytes of video data are recorded by both cameras during the 31 parabolas (22 s each) of each flight. For each observation direction, the cell is illuminated from the back, corresponding to the two sides perpendicular to the field of view (see Fig. 1 and Fig. 5). Note that illuminator 2 on the top of Fig. 1 should be located on the top of the cell, but has been turned over to enable the picture. In this open position, this illuminator masks the mirrors to obtain the required optical path between cameras and the cell (see top of Fig. 1). Each illumination is

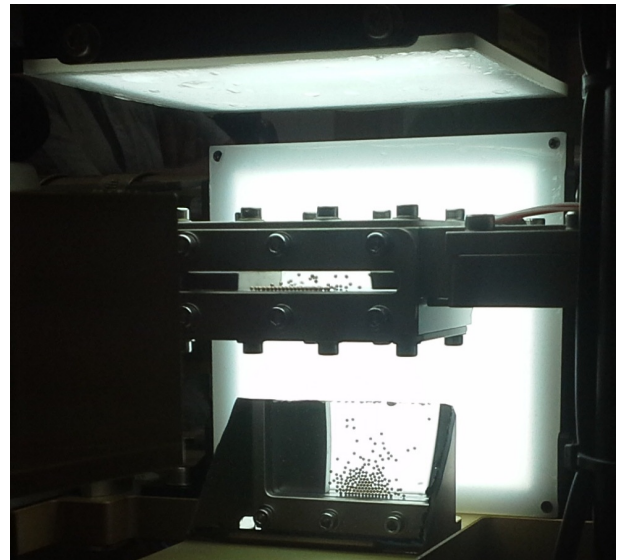


FIG. 5. On ground snapshot of the quasi-two-dimensional cell illuminated from the back, for each observation directions, via two diffuse LED with adjustable intensities. On the bottom, one can see the mirror enabling to take pictures from the bottom angle.

individually switchable, and its intensity adjustable. The light from LED is diffused and uniform along all field of view. Straight light coming from outside the instrument, reflections on cell glass walls, and bright spots on particles are minimized. We can select which illumination and which camera is activated (one of them or both).

F. Experimental rack in the aircraft

A photo of the experimental rack mounted in the aircraft is displayed in Fig. 4. The rack is made of Bosch Rexroth aluminium profiles and the instrument baseplate in aluminium. The total mass of the experimental rack is 176 kg (100 kg for the payload, 76 kg for the structure). The rack dimensions is $1.1 \text{ m} \times 1 \text{ m}$, and 0.67 m in height. Reinforcement bars of the rack in the aircraft main direction, and in the perpendicular direction, would resist in case of a hard landing of $9g$ and $3g$, respectively.

G. Low-gravity conditions

The VIP-Gran-PF instrument was used during five ESA Parabolic Flight Campaigns (PFC63 to PFC67) from November 2015 to November 2017. The first PFC has been dedicated to the testing of the instrument, the other ones to scientific issues. Low-gravity environment (about $\pm 5 \times 10^{-2}g$) is repetitively achieved by flying with the specially modified Airbus A310 Zero-G aircraft of Novespace¹⁷ through a series of parabolic trajectories which result in low-gravity periods, each of 22 s. A flight campaign lasts 3 days with 31 low-gravity parabolas per day.

H. Experimental parameters

Different experiments are performed with various forcing parameters and filling (number of beads and/or type of bead). Since the grains cannot be removed automatically from the cell, the different experiments should be classified according to increasing filling parameters. An overview of all relevant experimental parameters for the performed experiments can be found in Table I.

Symbol	Description	Value
N	Number of particles	–
R	Radius of the particles	1 to 5 mm
L	Distance between pistons	2 to 60 mm
h	Height of the cell	5 or 30 mm
V	Volume of the system	0.3 to 54 cm ³
ϕ	Packing fraction	0 to 60 %
A	Amplitudes of pistons	0 to 5 mm
f	Frequencies of pistons	0 to 50 Hz
φ	Phase shifts of pistons	0 to π

TABLE I. Table of the experimental parameters of the VIP-Gran instrument. In each row the description and the typical range of values are given for the different parameters. Note that L and h are defined in Fig. 2a.

III. SCIENTIFIC APPLICATIONS

The VIP-Gran-PF instrument is used since mid-2015. A wide variety of experimental situations can be studied in low-gravity conditions from dilute granular systems to dense assemblies. Several fundamental questions are notably addressed such as:

- How a granular gas (which is intrinsically dissipative due to inelastic collisions) deviates from the elastic limit of an ideal gas when dissipation increases?
- What is the phase diagram of dynamical states of such an out-of-equilibrium dissipative gas?
- What is the segregation mechanism in granular media composed of two types of particle species in low gravity?
- What is the behavior of a granular medium near the jamming transition (transition from fluid to solid) without confinement pressure of grains due to their own weight?
- How does sound propagate in dense granular media under low confining pressure (i.e. lower than the one provided by gravity near unjamming)?
- Does a dense granular medium display large-scale convection-like dynamics, like on Earth, when subjected to a thermal gradient-like forcing (i.e. two vibrating walls with different velocities)?

Some of these questions have been addressed in numerical works but never performed in experiments. Valuable experimental data will therefore be collected, for the first time ever, with the VIP-Gran instrument.

Since these open questions concern different experimental topics, numbers of particles, protocols, and time scales, different interchangeable cells are used to address them. As a proof of concept of the instrument, we will describe below some selected results obtained with this facility during ESA parabolic flight campaigns: (A) Granular gas dynamics, (B) clustering, and (C) segregation, convection and transport.

A. Granular gas dynamics

A granular gas displays striking properties compared to molecular gas: cluster formation at high enough density^{8,9}, anomalous scalings of pressure⁸ and collision frequency¹⁸, and non-Gaussian distribution of particle velocity^{10,19}. These differences are mainly ascribed to the dissipation occurring during inelastic collisions between particles. Continuous injection of energy is thus necessary to sustain a stationary state in this dissipative out-of-equilibrium system. This is usually performed experimentally by vibrating a container wall or the whole

container. For such boundary-forced system, the particle velocity distribution is not Gaussian as for an ideal gas, but a stretched exponential and is density dependent¹⁹. However, a spatially homogeneous forcing of a dilute granular gas leads to several major experimental differences (no cluster formation, exponential tail of the velocity distribution independent of the density)²⁰.

Here, we study with the VIP-Gran facility the analogue of the dynamics of Brownian particles moving in thermalized fluids. To wit, we placed three large intruders in a driven granular gas of smaller beads that act as a surrounding fluid (see Fig. 6). Experiments were carried out in the quasi 2D cell in order to allow an easy tracking of the intruders by the cameras. Thanks to image processing, we followed the motion of the large particles for different numbers of small ones and different driving parameters. Fig. 6 displays the trajectories of the three intruders obtained with our tracking. We then infer the mean square displacements of the intruders, and the Probability Density Function (PDF) of their velocities v_x along the x axis normalized by the piston velocity $A\omega$ (with $\omega = 2\pi f$). We observe a non-Gaussian distribution with heavy tails for high velocities. This tail vanishes as the number of small particles increases due to the dynamical confinement of large particles by small ones. In another set of experiments, we experimentally study how a granular gas deviates from the quasi-elastic limit (ideal gas) when dissipation increases in the system. One way to do that is to increase the volume of the container at a constant particle density all things being equal, as it was shown numerically²¹. By varying some parameters of the experiment (particle number and volume of the cell), one observes how the granular system deviates or tends to the quasi-elastic limit (not shown here).

B. Granular clustering

The transition from a gaseous regime to a cluster of particles for high enough density has been evidenced in a low-gravity experiment almost 20 years ago⁹. Numerical simulations have then reproduced this observation with the same parameters as in the experiment²². However, the parameters triggering this transition are far to be fully understood. By comparing the propagation time between two collisions and the relaxation time due to dissipative collisions, a 2D theoretical model based on an energetic approach predicts the marginal curve of the phase diagram separating gas- and solid-like regimes²³. Here, with the VIP-Gran facility, we study the clustering transition in 3D to obtain the full experimental phase diagram and to compare it with the predictions. Control parameters are the number of beads N , the mean distance L between vibrating pistons, the amplitude A and frequency f of the forcing. The packing fraction is then defined as $\phi = N\mathcal{V}_g/V \sim N/L$, where \mathcal{V}_g is the volume of a single grain and V the cell volume. Different parabolic

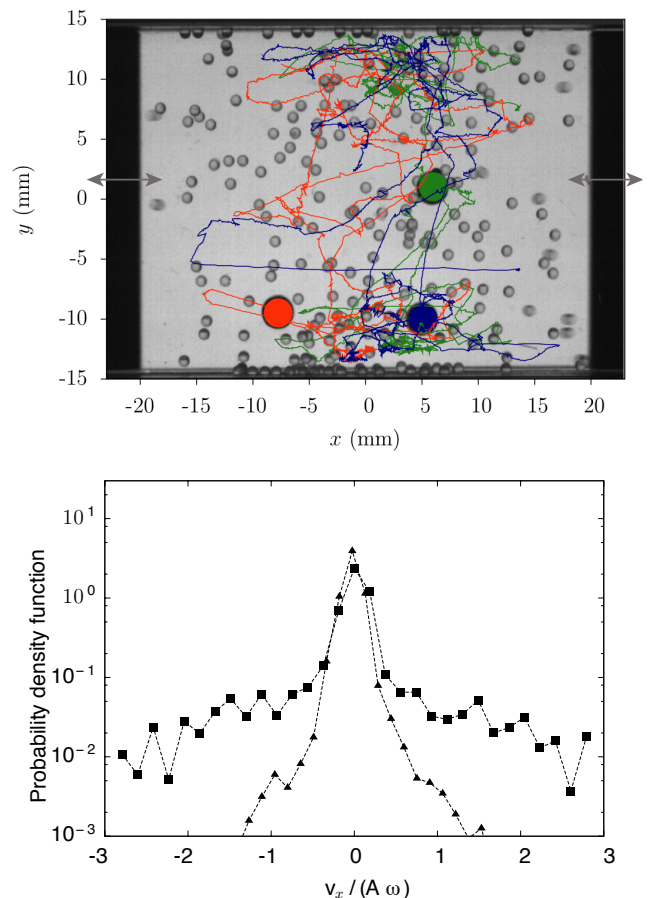


FIG. 6. Top: View of three large aluminium particles (5 mm in diameter, 176.6 mg in mass), immersed in a surrounding gas of thermalized small glass beads (1 mm in diameter, 4.08 mg in mass) in the quasi 2D cell. Both pistons (left and right black parts) vibrate sinusoidally in phase opposition. Each large particle is highlighted in a color (either orange, blue or green), as well as their respective trajectories. Bottom: PDF of the normalized velocities (along the x axis) of the intruders for (■) low and (▲) high numbers of small particles ($N_s = 50$ and $N_s = 300$, respectively). Snapshot taken from parabolic flight campaign ESA PFC66. Parameter range of the experiment: $f = 15$ Hz, $A = 5$ mm, packing fraction of small particles $\phi \in [1\%, 2.5\%]$ and $L = 45$ mm.

flight campaigns have been performed to cover the whole range of parameters. By means of the two perpendicular fields of view, and of image processing, the local density of particles and their velocities have been inferred in the 3D cell. As an example, Fig. 7 shows snapshots taken during PFC63 and PFC64. As one can see, starting from a gaseous regime, a cluster can be triggered by either increasing the packing fraction ϕ for a fixed volume (left column) or by increasing the volume for a fixed value of ϕ (right column). A regime of gas is discriminated from a cluster regime when the density distribution on both field of view is found to be uniform (gas) or nonuniform (cluster). Moreover, from all the PFC data, we have ob-

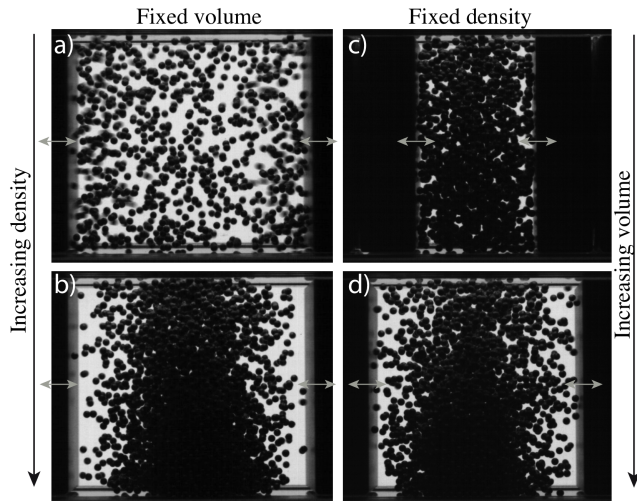


FIG. 7. Transition from a gas-like to a cluster regime of particles in low gravity in the 3D cell. Starting from a gaseous regime (top line), a cluster can be obtained (bottom line) by either (left row - PFC63) increasing the density $\phi = [1\% \text{ (a)}, 4\% \text{ (b)}]$ for a fixed volume ($L = 40 \text{ mm}$), or by (right row - PFC64) increasing $L = [12.5 \text{ mm (c)}, 27.5 \text{ mm (d)}]$ for a fixed value of $\phi = 6.5\%$. Both pistons (black parts) vibrates sinusoidally in phase opposition. Snapshots were taken during parabolic flight campaigns ESA PFC63 and PFC64 using the following forcing parameters $f = 20 \text{ Hz}$, $A = 2 \text{ mm}$.

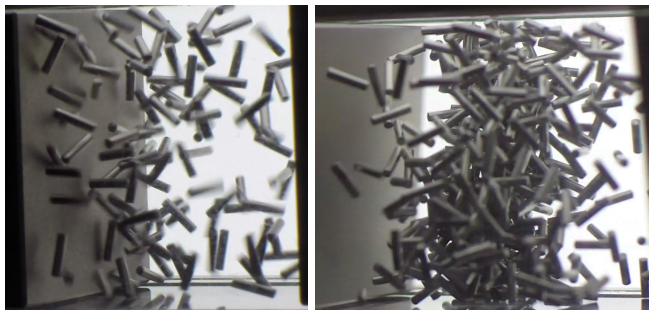


FIG. 8. Transition from a gas-like to a cluster regime of rods in low-gravity, when the packing fraction increases from 1% (top) to 3% (bottom). Experiments were realized in the 3D cell during the parabolic flight campaign ESA PFC66. Driving parameters and length in these snapshots are $f = 15 \text{ Hz}$, $A = 5 \text{ mm}$, and $L = 40 \text{ mm}$. Stainless steel rods (issued from bearings) are 1 mm in diameter and 4.3 mm length.

tained the full experimental phase diagram (not shown here). It is found to be well described by the model²³ except for strongly diluted and dense cases where additional phenomena are observed. Corresponding data will be deeply described elsewhere.

Another set of experiments performed within our facility concerns aspherical particle dynamics. In a dilute regime, its dynamics has been already studied in low-gravity showing non-Gaussian velocity distributions

and non-equipartition²⁴. Here, we use granular materials composed of rods presenting an aspect ratio of about 5. By increasing the packing fraction, we observe for the first time in low-gravity the transition between a gas-like and a cluster regime of rods as displayed in Fig. 8. Corresponding data will be deeply described elsewhere.

C. Granular segregation, convection and transport

Here we give few last examples of scientific applications that have been investigated with the VIP-Gran facility: Granular segregation, convection, and transport of particles in a partitioned cell under low gravity.

Segregation - On Earth, segregation of a granular medium composed of different particle species, is well-known (and often called the Brazil nut effect) and is due to different mechanisms related to gravity, either convection by friction of particles on boundaries²⁵, or percolation of small particles beneath large ones²⁶. In reduced gravity conditions, the segregation mechanism is unknown, and the relevant control parameters are not yet established³. The origin of large-scale particle segregation observed on the asteroid regolith surfaces is a matter of intense debate^{27,28}. Recently, collisional segregation has been proposed in this context²⁸ since a loose granular bed plays the role of impact absorbers either with gravity²⁹ or in absence of gravity³⁰.

Here, with the VIP-Gran facility, a mixture of small and large grains is subjected to vibrations in low gravity. Depending of the number N_s of small particles and the number N_l of large ones), different dynamics have been observed in the quasi 2D cell: In a dilute case, both particle types behave like gases homogeneously distributed (Fig. 9a). When additional small beads are injected into the cell, large beads are then forced to cluster in a strip in the center of the cell, leading thus to segregation (Fig. 9b). This effect is due to the dissipative nature of collisions. For high enough fillings (of both particle types), we observed for the first time in low gravity, a pattern in the center of the cell, constituted of alternatively strips of small and large particles³¹, as it was predicted numerically^{32,33} and theoretically³⁴.

Convection - On Earth, convection in granular media is related to spatial gradient of kinetic energy due to the inelastic collisions that, combined with gravity, produces a buoyancy-like force that, when dissipation is large enough, triggers convection^{7,35}. This mechanism should not be confused with air effect triggering convection rolls for submillimetric particles^{5,36}, or with convection induced by particle friction on boundaries for submillimetric particles^{3,25,37}. In low-gravity conditions, with no boundary or air effect, convection has only been observed numerically³². With the VIP-Gran facility, one can apply different phases and velocities on each of the pistons to mimic a thermal-like gradient forcing. The corresponding cold and hot walls are expected to drive the system into a convective-like motion due to the gener-

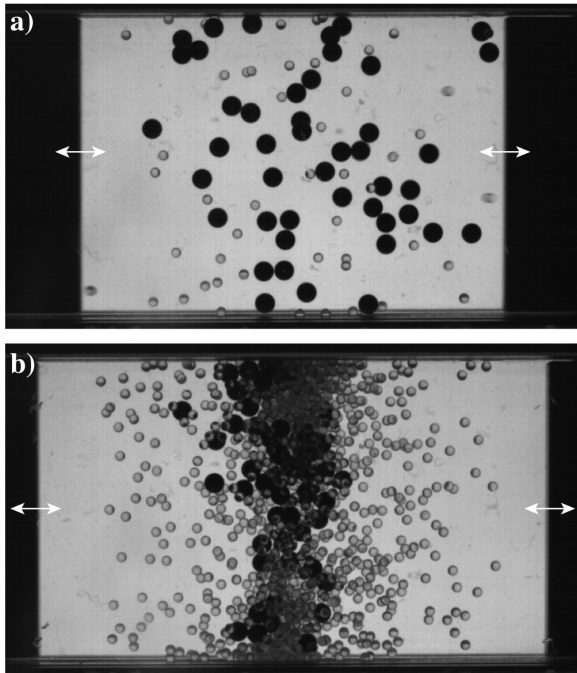


FIG. 9. Segregation of a mixture of large bronze and small glass beads in the 3D cell. In a dilute case ($N_L = 50$, $N_s = 50$), both particle types behave like a gas homogeneously distributed in the cell a). With additional small particles ($N_L = 50$, $N_s = 1000$), the latter force the large particles to accumulate in a stripe at the center of the cell, inducing thus segregation b). Both pistons (black parts) vibrates sinusoidally in phase opposition. Snapshots were taken during parabolic flight campaign ESA PFC65 with forcing parameters $f = 15$ Hz and $A = 5$ mm.

ated spatial gradients of the kinetic energy³⁸. Such large-scale convective motion have been observed in the 3D cell, during PFC experiments, within a mixture of large and small beads. However, the impact of the g -jitters on the phenomenon must still be clarified. This coarsening dynamics, and the appearance of vortex-like structures will be further analyzed. In future, much longer experiments with a better level of low gravity will be thus performed in space (see Sect. III D).

Handling a granular medium in low gravity - On Earth, pouring a granular material is an easy way to handle it. In absence of gravity, applying vibrations to the medium within partitioned cells with slits is a technique to manipulate it. However, the mechanisms leading to exchange of particles between the compartments are poorly understood in absence of gravity³⁹⁻⁴². Within a box made of two connected compartments, the separation of a granular system into a cold and dense region on the one hand, and a hot and dilute part on the other hand is usually called Maxwell Demon experiment. On Earth, the apparent intrusion of a Maxwell Demon has been investigated theoretically⁴³, experimentally⁴⁴ and numerically⁴⁵. The particle fluxes between compartments is related to the

ratio between the gravitational potential energy of particles and the granular temperature both taken at the altitude of the slit³⁹. In low gravity, this control parameter of the phase separation does not hold up. Thus, investigations in low-gravity experiments involving compartmented systems are foreseen for next PFCs within the VIP-Gran facility. This study will be complementary to the Chinese SJ-10 satellite mission⁴⁶, and will be guided by previous numerical simulations with mono-disperse⁴¹ or bi-disperse⁴² particles in compartmented systems in absence of gravity.

D. Future experiments in the International Space Station

The VIP-Gran facility was selected in early 2017 for flying on International Space Station (ISS) in 2019. The ISS version of the instrument is currently in development. Excellent low-gravity conditions ($\sim 10^{-5}g$) are indeed needed to avoid g -jitters, as observed in previous PFC notably for cooling and convection experiments. Long time duration experiments ($\gg 22$ s of PFC) are also needed to perform numerous iterative experiments to reach statistically convergent observations, or for phenomena with long transients. Since the beginning of the project, the VIP-Gran instrument has been conceived for an ISS usage and, accordingly, its design was orientated towards versatility, full automatization, and modularity through interchangeable cells. Several experiments not discussed here are planned with the ISS version of the instrument, such as dynamics of granular cooling (when the forcing is stopped)⁴⁷, sound propagation and rheology near the onset of jamming in dense granular media.

IV. CONCLUSION

To summarize, we have presented an experimental setup dedicated to the study of granular media in-low gravity environment in three- or two-dimensions. This instrument is capable of conducting experiments over a large range of granular packing fractions from diluted to dense regimes (up to approximatively 60%). The forcing mechanism is composed by two opposite walls of the cell driven by prescribed temporal stimuli (sine, single-pulse, quasi-static ramp, ...). The setup is instrumented by means of high-speed cameras in two perpendicular fields of view; accelerometers and impact sensors that allow to infer quantitative measurements. The cell volume, the number of particles, the amplitude, frequency and phase of the driving are control parameters. Our preliminary results with modular geometries, based on different interchangeable cells, demonstrate the versatility of our setup. Our system thus provides a unique facility to perform experiments on granular media in reduced gravity conditions. Several open questions are currently investigated with this facility related to granular gases, segregation, convection, and transport of grains in low-

gravity. Original scientific contributions as well as new applications for space exploration are thus expected.

An updated version of this facility is currently in development for the International Space Station to obtain excellent low-gravity conditions and a long duration of experimentations to study, notably, the cooling of a granular gas, convection, sound propagation in dense granular media under a ultra-low applied pressure, and rheology near the onset of the jamming transition without the confinement pressure of grains due to their weight.

V. ACKNOWLEDGMENTS

We thank M. Braibanti, O. Minster and V. Köhne from ESA for fruitful discussions and for the flight opportunity. VIP-Gran-PF was built by DTM Technologies™ (Modena, Italy). We thank A. Pellegrini, L. Recanatesi, and D. Santachiara for their experimental support on PFC64. We thank the support of Novespace during parabolic flight campaigns (PFC64 to PFC67). EO thanks Prodex (Belpo) for financial support. YG,CL,FP thank P. Evesque for collaboration, and thank CNES for both financial support and access to their PFC. This work was funded by ESA Topical Team No. 4000103461, CCN1 and CCN2.

- ¹B. Andreotti, Y. Forterre, and O. Pouliquen, *Granular Media: Between Fluid and Solid* (Cambridge University Press, Cambridge, 2013); J. Duran, *Sands, Powders, and Grains* (Springer-Verlag, New York, 2000); P. Coussot, *Rheometry of Pastes, Suspensions, and Granular Materials: Applications in Industry and Environment* (John Wiley & Sons, 2005)
- ²F. Spahn, J. Schmidt and M. Sremcevic, *Lect. Notes in Phys.* **557**, 507 (2000)
- ³C. Güttler, I. von Borstel, R. Schräpler and J. Blum, *Phys. Rev. E* **87**, 044201 (2013)
- ⁴Planetary Resources, Inc. (formerly Arkyd Astronautics) is an american start-up company aiming a profit-making mining of near earth asteroids. (<http://www.planetaryresources.com>)
- ⁵C. Laroche, S. Douady, and S. Fauve, *J. Phys. France* **50**, 699 (1989)
- ⁶S. Fauve, S. Douady, and C. Laroche, *J. Phys. Colloques* **50**, C3-187 (1989); F. Melo, P. Umbanhowar, and H. L. Swinney, *Phys. Rev. Lett.* **72**, 172 (1994)
- ⁷S. McNamara and S. Luding, *Phys. Rev. E* **58**, 813-822 (1998)
- ⁸E. Falcon, S. Fauve, and C. Laroche, *Eur. Phys. J. B.* **9**, 183 (1999)
- ⁹E. Falcon, R. Wunenburger, P. Evesque, S. Fauve, C. Chabot, Y. Garrabos, and D. Beysens, *Phys. Rev. Lett.* **83**, 2, 440 (1999)
- ¹⁰S. Luding, R. Caferio and H. J. Herrmann, *Driven granular gases*, in: *Granular Gas Dynamics*, T. Pöschel and N. Brilliantov (Eds.), *Lecture Notes in Physics* **624** (Springer Verlag, Berlin, 2003)
- ¹¹S. McNamara, *Phys. Fluids* **5**, 3056 (1993); I. Goldhirsch and G. Zanetti, *Phys. Rev. Lett.* **70**, 1619 (1993); N. Brilliantov, C. Salueña, T. Schwager, and T. Pöschel, *Phys. Rev. Lett.* **93**, 134301 (2004); S. Luding and H. J. Herrmann, *Chaos* **9**(3), 673-681 (1999); S. Miller and S. Luding, *Phys. Rev. E* **69**(3), 031305 (2004); S. Gonzalez, A. R. Thornton and S. Luding, *Europ. Phys. J. Special Topics* **223**(11), 2205-2225 (2014)
- ¹²S. McNamara and W. R. Young, *Phys. Fluids A* **4**, 496 (1992); S. Luding and S. McNamara, *Granular Matter* **1**(3), 113-128 (1998)
- ¹³G. Bossis, Y. Grasselli and O. Volkova, *J. of Phys.: Cond. Mat.* **16**, 18 (2004)
- ¹⁴C.H. Liu, and S.R. Nagel, *Sound in sand*, *Phys. Rev. Lett.* **68**, 2301 (1992); X. Jia, C. Caroli and B. Velicky, *Phys. Rev. Lett.* **82**, 1863 (1999); B. Gilles and C. Coste, *Phys. Rev. Lett.* **90**, 174302 (2003); S. Wildenberg, Y. Yang and X. Jia, *Granular Matter* **17**, 419 (2015); S. Wildenberg, A. Tourin and X. Jia, *EPL* **115**, 34005 (2016); R. K. Shrivastava and S. Luding, *Nonlin. Processes Geophys* **24**, 435-454 (2017); A. Merkel and S. Luding, *Int. J. Solids Struct.* **S 106-107**, 91-105 (2017); O. Mouraille and S. Luding, *Ultrasonics* **48**, 498-505 (2008)
- ¹⁵T. S. Majmudar and R.P. Behringer, *Nature* **435**, 1079 (2005); Majmudar, M. Sperl, S. Luding, R. P. Behringer, *Phys. Rev. Lett.* **98**, 058001 (2007); R. Harich, T. Darnige, E. Kolb and E. Clément, *Europhys. Lett.* **96**, 54003 (2011); D. Bi, J. Zhang, B. Chakraborty, and R. P. Behringer, *Nature* **480**, 355 (2011); J. Ren, J. A. Dijksman, and R. P. Behringer, *Phys. Rev. Lett.* **110**, 018302 (2013); H. Mizuno, L. E. Silbert, M. Sperl, *Phys. Rev. Lett.* **116**, 068302 (2016); S. Luding, *Nature Physics* **12**, 531-532 (2016); N. Kumar and S. Luding, *Granular Matter* **18**, 58 (2016)
- ¹⁶see <http://www.spacegrains.org> (latest news on VIP-Gran)
- ¹⁷Airbus A310 Zero-G is managed and operated by the French company Novespace from the Bordeaux-Mérignac airport (France)
- ¹⁸E. Falcon, S. Aumaître, P. Evesque, F. Palencia, C. Lecoutre-Chabot, S. Fauve, D. Beysens and Y. Garrabos, *Europhys. Lett.* **74**, 830 (2006)
- ¹⁹F. Rouyer, and N. Menon, *Phys. Rev. Lett.* **85**, 3676 (2000); W. Losert, D. G. W. Cooper, J. Delour, A. Kudrolli, and J. P. Golub, *Chaos* **9**, 682 (1999); J. S. Olafsen and J. S. Urbach, *Phys. Rev. E* **60**, R2468(R) (1999); A. Kudrolli and J. Henry, *ibid.* **62**, R1489 (2000); J. S. van Zon, J. Kreft, D. I. Goldman, D. Miracle, J. B. Swift, and H. L. Swinney, *ibid.* **70**, 040301(R) (2004); H.-Q. Wang, K. Feitosa, and N. Menon, *ibid.* **80**, 060304(R) (2009); S. Tatsumi, Y. Murayama, H. Hayakawa, and M. Sano, *J. Fluid Mech.* **641**, 521 (2009); Episov and Pöschel, *J. Stat. Phys.* **86**, 1385 (1997); Scholz and Pöschel, *Phys. Rev. Lett.* **118**, 198003 (2017)
- ²⁰E. Falcon, J.-C. Bacri, and C. Laroche, *Europhys. Lett.* **103**, 64004 (2013); *Phys. Rev. Fluids* **2**, 102601(R) (2017)
- ²¹S. Aumaître, J. Farago, S. Fauve and S. McNamara, *Eur. Phys. J. B.* **42**, 255 (2004)
- ²²E. Opsomer, F. Ludewig and N. Vandewalle, *Phys. Rev. E* **84**, 051306 (2011), *J. Phys.: Conf. Ser.* **327**, 012035 (2011)
- ²³E. Opsomer, F. Ludewig, and N. Vandewalle, *EPL* **99**, 40001 (2012)
- ²⁴K. Harth, U. Kornek, T. Trittel, U. Strachauer, S. Höme, K. Will, and R. Stannarius, *Phys. Rev. Lett.* **110**, 144102 (2013); K. Harth, T. Trittel, K. May, S. Wegner, and R. Stannarius, *Adv. Space. Res.* **55**, 1901 (2015)
- ²⁵J. B. Knight, H. M. Jaeger, and S. R. Nagel, *Phys. Rev. Lett.* **70**, 3728 (1993); R. Khosropour, J. Zirinsky, H. K. Pak, and R. P. Behringer, *Phys. Rev. E* **56**, 4467 (1997)
- ²⁶J. C. Williams, *Powder Technol.* **52**, 245 (1976); A. Rosato, K. J. Strandburg, F. Prinz, and R. H. Swendsen, *Phys. Rev. Lett.* **58**, 1038 (1987); H. M. Jaeger, S. R. Nagel, and R. P. Behringer, *Rev. Mod. Phys.* **68**, 1259 (1996)
- ²⁷N. Murdoch, P. Sánchez, S. R. Schwartz, and H. Miyamoto, in *Asteroids IV*, M. Patrick, F. W. DeMeo, and W. F. Bottke (Eds.), (University of Arizona Press, Tucson, AZ, 2015), p. 767
- ²⁸T. Shinbrot, T. Sabuwala, T. Siu, M. Vivar Lazo, and P. Chakraborty, *Phys. Rev. Lett.* **118**, 111101 (2017)
- ²⁹F. Pacheco Vázquez and S. Dorbolo, *Sci. Rep.* **3**, 2158 (2013)
- ³⁰S. McNamara and E. Falcon, *Powder Tech.* **182**, 232 (2008)
- ³¹E. Opsomer, M. Noirhomme, N. Vandewalle, E. Falcon and S. Merminod, *NPJ Microgravity* **3**, 1 (2017)
- ³²S. Luding, O. Strauss and S. McNamara, *Segregation of Polydisperse Granular Media in the Presence of a Temperature Gradient* in: *IUTAM Symposium on Segregation in Granular Flows 297-303*, A. D. Rosato and D. L. Blackmore (Eds.), (Kluwer Academic Publishers, 2000)
- ³³E. Opsomer, N. Vandewalle, M. Noirhomme, and F. Ludewig, *Eur. Phys. J. E* **37**, 115 (2014)

- ³⁴D. Serero, S. H. Noskowitz, M. L. Tan, and I. Goldhirsch, Eur. Phys. J. Special Topics **179**, 221 (2009)
- ³⁵R. Ramírez, D. Risso, and P. Cordero, Phys. Rev. Lett. **85**, 1230 (2000); R. D. Wildman, J. M. Huntley, and D. J. Parker, Phys. Rev. Lett. **86**, 3304 (2001); E. Khain and B. Meerson, Phys. Rev. E **67**, 021306 (2003); D. Paolotti, A. Barrat, U. Marini Bettolo Marconi, and A. Puglisi, Phys. Rev. E **69**, 061304 (2004)
- ³⁶H. K. Pak and R. P. Behringer, Phys. Rev. Lett. **71**, 1832 (1993); K. Kumar, E. Falcon, K. M. S. Bajaj, and S. Fauve, Physica A **270**, 97 (1999); A. Garcimartín, J. M. Pastor, R. Arévalo, and D. Maza, Eur. Phys. J. Special Topics **146**, 331 (2007)
- ³⁷N. Murdoch, B. Rozitis, K. Nordstrom, S. F. Green, P. Michel, T.-L. de Lophem, and W. Losert, Phys. Rev. Lett. **110**, 018307 (2013)
- ³⁸P. Eshuis, K. van der Weele, M. Alam, H. J. van Gerner, M. van der Hoef, H. Kuipers, S. Luding, D. van der Meer and D. Lohse, Granular Matter **15**(6), 893-911 (2013)
- ³⁹N. Isert, C. C. Maaß, and C. M. Aegerter, Eur. Phys. J. E **28**, 205 (2009)
- ⁴⁰J. J. Brey, F. Moreno, R. Garcia-Rojo, M. J. Ruiz-Montero, Phys. Rev. E **65**, 011305 (2001)
- ⁴¹Y. Li, M. Hou, and P. Evesque, J. Phys.: Conf. Ser. **327**, 012034 (2011); E. Opsomer, M. Noirhomme, N. Vandewalle, and F. Ludewig, Phys. Rev. E **88**, 012202 (2013); M. Noirhomme, E. Opsomer, N. Vandewalle, and F. Ludewig, Eur. Phys. J. E **38**, 9 (2015)
- ⁴²W. Wang, Z. Zhou, J. Zong, and M.-Y. Hou, Chin. Phys. B **26**, 044501 (2017)
- ⁴³J. Eggers, Phys. Rev. Lett. **83**, 5322 (1999)
- ⁴⁴K. van der Weele, D. van der Meer, M. Versluis, D. Lohse, Europhys. Lett. **53**, 328 (2001)
- ⁴⁵A. Barrat and E. Trizac, Mol. Phys. **101**, 1713 (2003); M. Hou, H. Tu, R. Liu, Y. Li, K. Yu, P.-Y. Lai, and C. K. Chan, Phys. Rev. Lett. **100**, 068001 (2008); S. Shah, Y.C. Li, F. F. Cui, Q. Zhang, P. Evesque, and M. Hou, Chin. Phys. Lett. **29**, 034501 (2012)
- ⁴⁶M. Hou, *Private Communication*
- ⁴⁷C. C. Maaß, N. Insert, G. Maret, and C. M. Aegerter, Phys. Rev. Lett. **100**, 248001 (2008); Y. Grasselli, G. Bossis, G. Goutallier, EPL **86**, 60007 (2009); S. Tatsumi, Y. Murayama, H. Hayakawa, and M. Sano, J. Fluid Mech. **641**, 521 (2009); D. Heißelmann, J. Blum, H. J. Fraser, and K. Wolling, Icarus **206**, 424 (2010); K. Earth, T. Trittel, S. Wegner, and R. Stannarius, EPJ Web Conf. **140**, 04008 (2017)