GAS-CLUSTER TRANSITION OF GRANULAR MATTER UNDER VIBRATION IN MICROGRAVITY

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Abstract

We report an experimental study of a "gas" of inelastically colliding particles, excited by vibrations in low gravity. In the case of a dilute granular medium, we observe a spatially homogeneous gas-like regime, the pressure of which scales like the 3/2 power of the vibration velocity. When the density of the medium is increased, the spatially homogeneous fluidised state is no longer stable but displays the formation of a motionless dense cluster surrounded by low particle density regions.

In this paper, we report a study of the kinetic regime of a granular medium, fluidised by vibrating its container in a low gravity environment. The motivation for low gravity is to achieve an experimental situation in which inelastic collisions are the only interaction mechanism. The aim of the experiment is to observe new phenomena which result from the inelasticity of the collisions and are thus absent in a usual gas. In the dilute case, we show that the pressure of a granular gas scales like the 3/2 power of the vibration velocity. When the density of the medium is increased, we observe for the first time that an ensemble of solid particles in erratic motion interacting only through inelastic collisions can generate the formation of a motionless dense cluster. In the present case, this occurs as soon as the mean free path between two grain-grain collisions becomes smaller than the cell size. Gaseous conditions are then only observed for a system of solid particles in the Knudsen regime. These experiments tend also to demonstrate that the statistics of grain velocity does not obey the classical Boltzmann distribution even under such restrictive conditions.

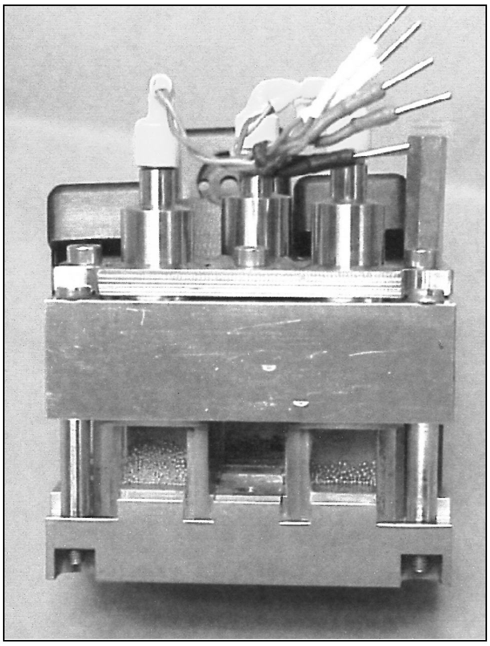

Figure 1: The three 1cm^3 cubic experimental cells filled with (respectively from left to right) 0.281 g , 0.562 g and 0.8915 g of bronze spheres of 0.3-0.4 mm diameter, (solid fraction 3.2% , 6.4% and 10.1%).

3 of the six walls of each cell were in metal and linked to the electric ground in order to avoid as much as possible any electrostatic charge problem; the top side was closed by a piezoelectric pressure sensor (PCB 106B50) and the two other windows situated in the front and on the left or right side were in sapphire in order to allow visualisation and illumination respectively.

Illumination was achieved using three distinct photodiodes, one for each cell, emitting either continuously when vibration frequency was smaller than 30Hz, or at a rate of 14 Hz (28Hz) when mechanical vibration was 30 Hz (60 Hz); the pulse duration was 1ms in these two last cases. (This was partly described in [2] only). The two left hand cells were unlighted from the left and the right one from the right.

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This seems to be different from what has been obtained previously in a pedagogical experiment sponsored by CNES under micro gravity environment [1]; so more experiments are needed to confirm this result [2].

Indeed, vibrated granular media display already striking fluid-like properties on Earth: convection and heaping, period doubling instabilities [3, 4], and parametric extended [4] or localised [5] surface waves. When the vibration is strong enough, the granular medium undergoes a transition to a fluidised state which has been tentatively described using kinetic theory [6] with a "granular temperature", *i.e.* a mean kinetic energy per particle. Fluidisation by vibrations bas been studied experimentally [7,8] and numerically [8,9], but no agreement has been found so far for the dependence of the granular temperature on the amplitude and the frequency of external vibrations [10-12].

However, one of the most interesting properties of such "granular gases" is the tendency to form clusters. Although this has probably been known since the early observation of planetary rings [13], there exist only a few recent laboratory experiments which display cluster formation [14], but the coherent friction force acting on all the particles was far from being negligible. Various cluster types in granular flows have also been observed numerically [15]. The mechanisms of cluster formation are an active subject of research that still deserve more study because of its relevance to technical, astrophysical [16], or geophysical [17] applications of granular media. At a more fundamental level, it is of a primary interest to understand the new qualitative behaviours due to inelasticity of collisions in kinetic theory.

Experiment:

The Mini-Texus 5 space-probe was launched from Esrange (Nothern Sweden) on a Nike-Improved Orion rocket with 3 cubic containers on board, 1 cm^3 in inner volume, with clear sapphire walls. Each cell is filled, respectively, with 0.281, 0.562 and 0.8915 g of 0.3-0.4 mm in diameter bronze spheres (solid fractions: 3.2%, 6.4% and 10.1%). Thus, the total number of particles in each cell is about 1420, 2840 and 4510, corresponding to roughly 1, 2 and 3 particle layers at rest. An electrical motor, with eccentric transformer from rotational to translational motion, drives the vessels sinusoidally at frequency f and maximal displacement amplitude A in the ranges 1 to 60 Hz and 0.1 to 2.5 mm respectively. The vibrational parameters during the time line are listed in Table I [2]. The vessel containing the three cells filled with bronze beads is displayed in Fig. 1 together with the three pressure gauges.

Experiment number	**Time segment** (s)	**Amplitude** A (mm)	**Frequency** f (Hz)	**Velocity** V (cm/s)	**Acceleration** Γ (g unit)
1	23 - 36	0.1	3	0.2	0.004
2	46.8 - 52	2.5	1	1.6	0.01
3	52.3 - 67.3	2.5	3	4.7	0.09
4	76.5 - 84.5	0.3	30	5.6	1.1
5	87 - 100	0.1	60	3.8	1.4
6	103 - 116.5	0.3	60	11.3	4.3
7	120 - 130	1	60	37.7	14.5
8	138.5 - 148	2.5	30	47.1	9
9	151 - 180	2.5	60	94.2	36.2

Table 1: Vibrational parameters during the 200 s of low gravity. Time segment is the duration of each experiment at fixed amplitude and frequency without taking into account the transient states. $V = 2\pi Af$ and $\Gamma = 4\pi^2 Af^2/g$ are respectively the velocity amplitude and the dimensionless acceleration amplitude of the vessels, $g=9.81 m/s^2$. Data from experiment 1 had a poor signal to noise ratio. Data from experiment 9 were misleading since the space-probe was beginning its coming into the stratosphere.

Motion of particles was visualised and recorded by an SWMO39 CCD camera, fixed in the frame of the space-probe, that captures 742 x 582 pixel images with a 40 ms exposure time. Each cell was illuminated by one led lighting at right angle from the observation. Continuous illumination was used when mechanical-excitation frequency was smaller than 30Hz. However, the amplitude of the cell- and the bead- motions became large during the exposure time for the larger 30Hz and 60 Hz frequencies; stroboscopic illumination of 1ms duration was then used to increase clearness; its working frequency was respectively 14 Hz and 28 Hz for the driving mechanical frequencies of 30 Hz and 60Hz. Accelerations were measured by piezoelectric accelerometers (PCB 356AO8) screwed in the shaft in a triaxial way. Typical output sensitivities in the vibrational direction and in the perpendicular directions were, respectively, 0.1 and 1 V/g, $g = 9.81 m/s^2$ being the acceleration of gravity. A piezoelectric pressure sensor (PCB 106B50), 1.53 cm in diameter, was fixed on the "top" of each cell. The accelerometer orientation, in the direction of vibration, was such that its head was pointed perpendicular towards pressure sensor surface. Typical pressure sensor characteristics were a 0.72 mV/Pa output sensitivity, a 20 Pa/g acceleration sensitivity, a 40 kHz resonant frequency, and a 8 µs rise time.

The component of the pressure signals due to the sensor sensitivity to acceleration has been removed by signal processing using Fourier transform. The firing of the engine, the stabilisation of the rocket on its parabolic trajectory and the despinning of the rocket lasted roughly 90 s, the apex being 150 km above the Earth. Then, the output signals of acceleration and pressure sensors were transferred to Earth in real time with a 2 kHz sampling rate during the 200 seconds of low gravity environment (about 10^{-5} g) before parachute opens, the first 20 s of the experiment being without vibration to let the granular medium relaxing.

Results and discussion:

Fig.2 displays what can be observed in the three different cells when excited at f =30Hz , with A=2.5mm, and at two different phases of the vibration cycle: Fig. 2(a) (*resp.* Fig. 2(b)) corresponds to a maximum "upward" (*resp.* "downward") velocity (see also Fig. 3). The density is decreasing from the left to the right. In the most dilute case, the particles move erratically and their distribution is roughly homogeneous in space (there is a depletion close to the boundary moving away from the particles). In the two denser cases, a motionless dense cluster in the reference frame of the camera, i.e. of the space-probe (black central region of the photographs) is surrounded by lower particle density regions. The sphere surrounding the cluster are in motion, mainly in the part of the vessel close to the boundary moving toward the granular medium. We thus observe that at high enough density, the spatially homogeneous gas of particles undergoes an instability which leads to the formation of a dense cluster. Note that the left and the middle (*resp.* right) cells are illuminated from the left (*resp.* right) side. The apparent increase in cluster size is an artefact due to light diffusion which reduces the enlightenment as the light penetrates deeper in the cell (see Fig. 2).

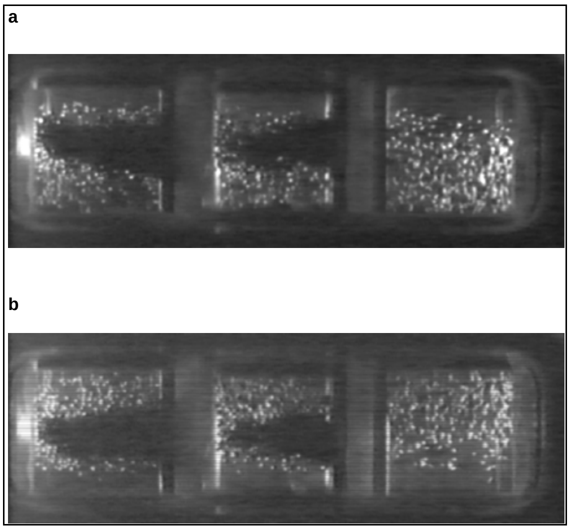

Figure 2: transition between gas behaviour (right) to cluster behaviour.
The three cells: right the most dilute cell; left: the densest cell
(a) maximum "upward" velocity
(b) maximum "downward" velocity
The pressor sensor is on "top" of the cells.
The parameter of vibration was amplitude A=2.5 mm, frequency f=30 Hz

The difference between the two kinetic regimes, homogeneous and clustered, is also apparent on the pressure signals displayed in Fig. 3. In the dilute case (upper curve in Fig. 3), the time recording of the pressure, measured at the "top" wall (see Fig. 1), shows a succession of peaks corresponding to particle collisions with the wall. In the two denser cases, the pressure involves a component in phase with the acceleration imposed to the vessel (lower curve in Fig. 3). Note that in the case of intermediate density (second signal from the top), both the pressure peaks and the component in phase with the acceleration are visible. However, the amplitude of pressure fluctuations is smaller than for the dilute case, although the particle number is larger; the reason is that most particles are in the cluster, which, as can be seen in the video recordings, stays away from the walls except for the largest amplitude of vibration. The pressure component, in phase with the acceleration, traces back to the grains in the low density region between the cluster and the walls. It shows that in the densest case, the motion of these particles is coherent with the vibration, as already observed in numerical simulations [18]. In the case of intermediate density, the vibration generates both a coherent pressure oscillation and incoherent motions displayed by the random pressure peaks in the signal.

We now consider the dilute case for which the spatially homogeneous fluidised regime is stable. Particles move erratically and the pressure signal displays a succession of peaks. Note that the pressure being measured on the whole surface of the "top wall", a peak does not correspond to the collision of a single sphere, which would lead to an impact duration of about 2 μs [19] and is hardly resolvable by the transducer. These peaks correspond to a collective collision leading to a much longer typical impact duration of about 2 ms (thus resolved by the 2 kHz sampling rate). Bursts of peaks occur roughly in quadrature with the acceleration but the number of peaks in each burst, their amplitude, and the duration of each burst are random (see Fig. 3). Note the small distortions in the acceleration signal, occurring at the same times as the pressure peaks. The distortions near the extrema of the acceleration signal are generated by the mechanical driver at full stroke. Assuming a roughly homogeneous particle distribution, one can estimate that each peak in the pressure recording of Fig. 3 involves about 150 collisions. This shows that the mean duration between successive collisions is comparable to the transducer rise time. Besides, the probability of multiple collisions within the duration of a single collision is small. Thus, we do not expect the transducer response to be biased by multiple collisions along its surface within a short time period. As said above, the pressure signal in Fig. 3 is averaged on a time interval long compared to the duration of a single collision. It is thus proportional to the sum of the impulses of the successive collisions. Consequently, it depends on the mass and the incident velocities of the particles, but also on the elastic properties of both the particle and the transducer through the restitution coefficient.

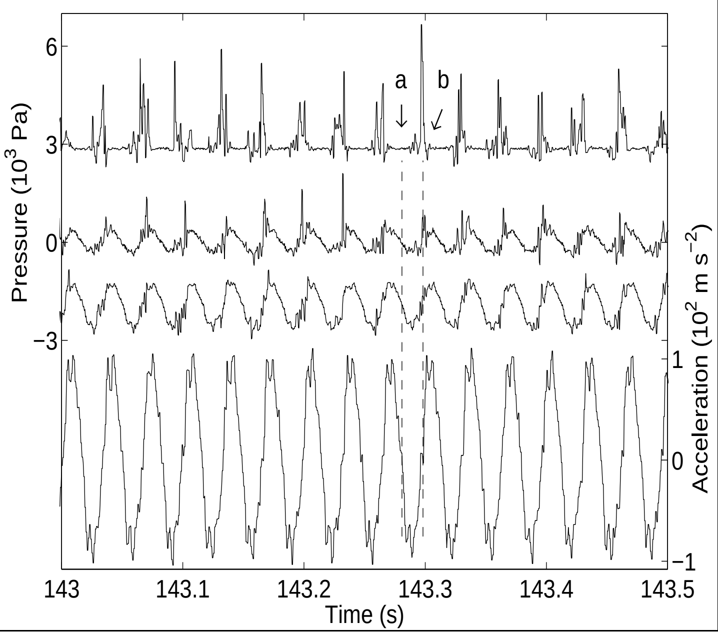

Figure 3: Granular pressure variations as a function of time (s) for the three cells of Figs. 1 & 2, under same conditions as Fig. 2, i.e. experiment # 8 in Table I .
From the upper to the lower curve: pressure signal in the dilute sample; pressure signal in the medium dense sample; pressure signal in the densest sample; acceleration in the direction of vibration. Letters a and b refer to the times when pictures in Figs. 2.a and 2.b have been taken. Pressure curves are shifted vertically for clarity.
Spikes of top curve demonstrate the incoherent motion of the granular gas in the dilute regime. However each spike correspond to a series of grain-wall collisions.

Fig. 3 demonstrates also the supersonic character of the cell vibration speed compared to the thermal agitation of the beads since the motion of the cell is so fast that a depletion zone, where no bead can be found, is generated periodically. This demonstrates that the largest speed of grains is always much smaller than the maximum amplitude of the vibration speed. These results remain valid also for the other values of the vibration parameters A and f whose Fig. 4 is an example.

"Supersonic" excitation and Knudsen regime of the "gaseous" phase:

A deeper analysis of Fig. 2 alone could lead to wrong conclusions: let us remark that in the densest cells of Fig. 2, one can see the existence of a sharp discontinuity of the bead density on the upper (*resp.* lower) parts of Fig. 2a (*resp.* 2b). The limit of the black zone corresponds, at least approximately, to the minimum (*resp.* maximum) height of excursion of the top (*resp.* bottom) wall of the cell. Above (below) this zone one sees a less dense zone which diffuses light. It seems to correspond to grains which have moved already from the dense compacted zone and have invaded the vacuum zone generated by the cell motion; so, this invasion seems to correspond to the expansion of the dense medium. As this expansion is much slower than the motion of the wall, it generates the large depletion zone which contains no grain in between the granular medium and the "top" (*resp.* "bottom") wall. This demonstrates of the supersonic nature of the cell motion, which moves then roughly at Mach 3 or so. Looking at Fig. 2b (2a), one can conclude that the time needed for the expansion burst to reach the wall is approximately 3T/2 , where T is the period of mechanical excitation. When contact is achieved between the gaseous grains and the wall, it shall generate burst of pressure. This is indeed what is observed on Fig. 3, for the two less filled samples for which burst of pressure signal is recorded when the acceleration is positive and increasing, i.e. during 3T/2 and 2T.

However study of other amplitudes of vibration confirms only partly these results: indeed, the granular temperature is such that the sound speed in the gas is always smaller than the maximum cell velocity, so that a depletion zone with no grain near the moving wall is observed periodically. So, the excitation is always of the *supersonic kind*. On the other hand, for small amplitudes of vibration, the contact between the dense medium and the moving walls is not a direct contact, but occurs through a loose gas of grains in *Knudsen regime* which takes in sandwich the dense cluster and which maintains the dense cluster in the centre of the cell, far from the wall, as shown in Fig. 4 . So, the formation of a dense cluster in denser samples is not demonstrated by Fig. 2 but by Fig. 4. So if conclusions of [2] are correct concerning the existence of a dense cluster in the densest regimes, their proof needs other data than those reported in

Fig. 1 of [2].

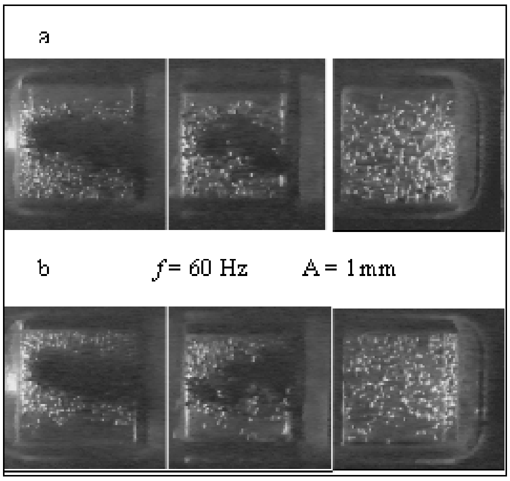

Figure 4: transition between gas behaviour (right) to cluster behaviour. Parameters of vibration are amplitude A=1mm, frequency f=60 Hz. The three cells: right the most dilute cell; left: the densest cell.

(a) "upward" velocity.
(b) "downward" velocity .

Contrarily to Fig. 2 case, the dephasing between the two images is not π exactly here.

The pressor sensor is on "top" of the cells.

Pressure in the dilute cell:

As above mentioned already, one can obtain from Fig. 3 the proportion of time during which particles are in contact with the sensor in the dilute cell. It is roughly T/4. This signal displays large fluctuations whose statistics is reported in Fig. 5 in the form of the probability density functions of pressure fluctuations, measured directly by the pressure sensor. Rescaling procedure of these data was performed in [2] to obtain a single curve, indicating that the probability density functions roughly scale like $V^{3/2}$ so that the pressure should scale also roughly like $V^{3/2} =(2\pi\, A\, f)^{3/2}$, where V is the maximal vibration velocity of the vessel, ranging from 1.6 to 47 cm/s.

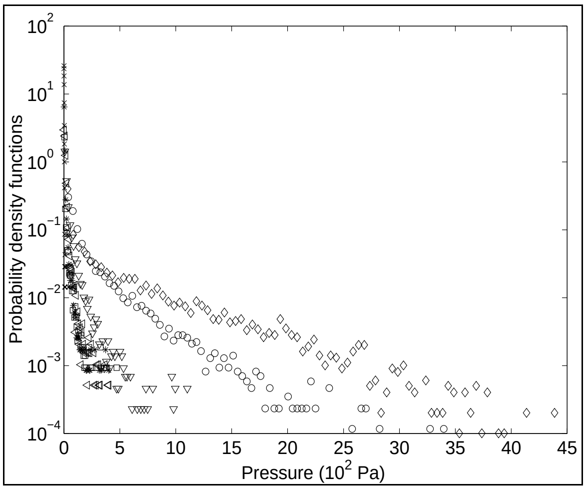

Figure 5: Probability density functions of pressure fluctuations in the dilute cell, for the different vibrational parameters of Table I. Semi-log plots.

Experiment #2 (x); #3 (☐); #4 (*); #5 (◁); #6 (); #7 (○); #8 ().

Same symbols are used in Fig. 3 of ref. [2].

Discussion & conclusion:

Pressure p is a much easier quantity to measure experimentally than granular temperature and, for a spatially homogeneous density, one expects their mean values to be proportional. However, this is more complicated when the system is inhomogeneous. Denoting ε the restitution coefficient, $\rho(v,x,t)$ the bead density at time t and position x, having the speed v_x in the direction of vibration and labelling $v_o(t)$ the gauge and cell speed, one shall have:

$$p_x(t)=\Sigma_{beads}\,\rho(v_x,x_o,t))\;m(1+\varepsilon)[v_x(t)-v_o(t)]^2 \qquad (1)$$

where m is the bead mass and $x_o(t)$ the gauge position; this makes difficult to analyse the present "*supersonic*" excitation case. So, it may be more convenient to try a dimensional analysis which smoothes out the inhomogeneous nature of the system, writing the mean kinetic energy per particle E/N as:

$$E/N = m\, f^2 A^2\, G(\varepsilon,N,A/L,R/L) \qquad (2)$$

where G is an arbitrary function of dimensionless parameters, with R, the radius of the particles, L the length of the vessel. Note that one should take into account different restitution coefficients for the particle-particle and the wall-particle collisions, but that this would not modify the frequency dependence of the granular temperature. Consequently, in low gravity, one expects the granular temperature T or the mean pressure p to be proportional to V^2, instead of the $V^{3/2}$ found experimentally; this means that another dimensionless parameter involving a new velocity scale shall be considered in Eq. (2); the dependence of ε on the impact velocity could provide this additional parameter; since $E/N \propto V^2/(1-\varepsilon)$, this implies that $1-\varepsilon \propto V^\alpha$ with $\alpha=1/2$; indeed, ε varies between .97-.87 in our experimental range [20]. Similar results [7-12] finding scaling laws for the granular temperature, in the range $V^{4/3}$ -V^2 exist already; but they were obtained with gravity and cannot be conclusive since an additional dimensionless parameter $A f^2/g$ is involved in Eq. (2).

More generally, (i) pressure measurement in fluidised granular matter is performed locally, near a boundary, where the pressure distribution is quite inhomogeneous and where Eq. (2) is not adequate; so correct interpretation requires the use of Eq. (1) . (ii) The "supersonic" nature of the excitation is a strong limitation to simple interpretation. (iii) Local measurements restrict the investigation to what happens in average in a single layer and corresponds to some kind of a Knudsen regime (due to the inhomogeneity). One can reinterpret data on vertically vibrated beds on Earth [21] in this scheme and consider that the top layer only has a well measured temperature since its density varies as $\exp\{-gz/(kT)\}$, the temperature of the lower grains remaining unknown.

In conclusion, we have reported a 3-D experiment of a granular medium fluidised by sinusoidal vibrations in low gravity environment. When the density of the granular medium is increased, we clearly show that an ensemble of particles in erratic motion interacting only through inelastic collisions spontaneously generates the formation of a motionless dense cluster.

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