Scientific Goals of the Topical Team on Vibration in Granular Media: (The physics with the future VIP_Gran Instrument)

Pierre EVESQUE[1], Angel GARCIMARTIN[2], Diego MAZA OZCODI[2], Nicolas VANDEWALLE[3], Yves GARRABOS[4], C. LECOUTRE[4], Daniel BEYSENS[5], Xiaoping JIA[6], Meiying HOU[7]

[1] Laboratoire MSSMat, Ecole Centrale de Paris, UMR 8579 CNRS, 92295 Châtenay-Malabry Cedex, France, pierre.evesque@ecp.fr
[2] University of Navarre, Pamplona, Spain, angel@fisica.unav.es, dmaza@unav.es
[3] GRASP, Université de Liège, Belgique, nvandewalle@ulg.ac.be
[4] ESEME, Institut de Chimie de la Matière Condensée de Bordeaux, CNRS, 33608 Pessac Cedex, France, garrabos@icmcb-bordeaux.cnrs.fr
[5] ESEME, PMMH, CEA-ESPCI et Universités Paris 6 et Paris 7, 10 rue Vauquelin, 75231 Paris Cedex 05, France, daniel.beysens@espci.fr
[6] Université Paris-Est, LPMDI, UMR 8108 CNRS, 77454 Marne La Vallée, France, jia@univ-mlv.fr
[7] Chinese Academy of Science, Beiying, China, Meiying Hou, mayhou@aphy.iphy.ac.cn

Abstract

This paper describes goals of research and some example of recent results on the dynamics and the statistical mechanics of an ensemble of real particles that dissipates due to collision, i.e. ball-wall and ball-ball collisions, studied in micro-gravity. Special care is taken to study the limits of little interaction between the balls because of their small density number (Knudsen regime) and the limit of strong interaction when the mean free path between 2 ball-ball collision is less than the cell size. It turns out that the physics of these dissipative systems is non extensive and generates heterogeneities. The question of transporting and managing grains is asked, taking as an example the Maxwell's demon. Comparison with different limiting cases will be achieved, i.e. with dissipative billiard model and with the statistical mechanics of gas or of liquid.

1. Introduction

Although studied for several centuries [1,2)] due to their applications, granular media have recently received increasing attention from physicists[3)] and refs of [3)]. Granular media exhibit a wide range of behaviors, from solid-like to gas-like through liquid-like [see refs in [3), 4)]], depending on the dynamic coupling of the particles with the surrounding media and the intensity of the mechanical excitation. Dynamical decoupling between the particles and the surrounding media is achieved by using low pressure – low density fluid, such as air at atmospheric pressure, or even a vacuum. This is this condition which will be discussed here exclusively, while we expect to be able to study coupling with liquid also in a second time.

In such a low density fluid, the solid particles can be considered as isolated bodies between each collision. One of the most interesting properties of granular gas is then the dissipative nature of the particle-particle interactions (inelastic collisions). The usual techniques and results of statistical mechanics can then be used to analyze the “thermo-statistics” of a dissipative gas, at least in principle. Then the validity of the extension of these laws to granular dissipative systems can be tested.

From an experimental point of view, in order to study its properties in a steady state, it is necessary to bring to the gas of particles a steady amount of kinetic energy that balances the dissipative losses. Mechanical vibrations are a common way to inject this energy and to keep constant the “temperature”. here we will use linearly polarized vibrations.

From another viewpoint, a large part of the natural environment of human being is made of granular materials. Such materials enter then at some stage of most industrial processes and of most human activity; hence, their presence and/or use is probably unavoidable in an inhabited spacecraft dedicated to a long term travel to explore the universe. Under these conditions, it is urgent to start investigating their physics and the safety conditions they require in weightlessness, since they are quite dangerous to breath and they can block any mechanical command.

At last, the present results are complementary from others on granular matter which have been developed by other space agencies, which study either segregation due to shear in dense granular flow [5)], the rheology of confined soils and grains in quasi-statics and under loose confinement [6)] and the behavior of granular matter in reduced gravity, dedicated to Lunar and Martian exploration and exploitation.

2. Main goals of research

So, the aim of this research is to study the dynamics and the statistical mechanics of an ensemble of real particles that dissipates due to collision, i.e. ball-wall and ball-ball collisions. Special care is taken to study the limit of weak interaction between the balls due to their small number (Knudsen regime) and the limit of strong interaction when the mean free path between 2 balls collision is much less than the cell size.

Different ball sizes will be investigated, as well as different cell shapes and cell sizes and the effect of parameter of vibration. Attention will be paid to properties of mixing and segregation.

Comparison with different limit cases will be achieved, i.e. with dissipative billiard model and with the statistical mechanics of gas or of liquid. Also, difference between 2-d vs 3-d behaviours will be studied. Also one will test if vibration can generate convection in vibration, as it does on earth.

As a matter of fact, beyond all this, the main important question which remains to be answered is to know whether one reaches a stationary system by exciting a granular medium with permanent vibration or the system becomes non steady in some range of parameter, and the ball trajectories are not ergodic. What kind of chaotic regime can be generated in such cases? This will fix the limit of our ability to control and manipulate granular medium, in microgravity. This also forces to study and to characterize the behaviors and their evolution at long time.

Indeed, an important question of interest is how to manipulate a collection of grains in micro-gravity when contact with boundary is not certain: how can one force the grains to go from one side to another one, or from one box to an other one? how one can force the grains to evacuate from a container. Can one extend the concept of Maxwell's demon? How sensitive the system is to g-jitter?

Another subject of interest is the segregation mechanism of binary mixtures (particles species of different sizes, shapes or densities). On Earth, segregation is frequently observed, but there is no unified theory for this phenomenon, and even the relevance of the description in terms of minimisation of interaction energy is still an open question. This "hot" scientific problem has been the object of micro-gravity research funded by NASA [5] and the Japanese Space Agency [7] in an industrial context. Since the experiment by NASA consists in shearing a rather-dense binary granular mixture in low gravity, the experiments proposed here to vibrating a granular medium are complementary.

3. Experimental method

The experimental method is sketched on **Fig. 1** below: a cell containing grains is vibrated (amplitude A, frequency f) and one observes the grains moving. An injector may allow to fill the cell with grains; pressure and impact gauges will be other possible diagnostics available. The frame rate of the fast camera can be adjusted at will to allow recording as fast as 1000 frames/s or as slow as few frames a minutes. Amplitude can be as large as few centimeter to allow the study of impact of clusters with plate or of a sphere with a granular medium.

So, typical experimental range is f=[0.1Hz-40Hz], A=[0.1mm-40mm], with some limitation due to intensity of vibration $\Gamma=4\pi^2f^2A$, and to power supply. Different cells will be used with different shapes and sizes, up to 60 mm length. Grains made of different materials, with different shape and size will be studied, with typical diameter ranging from 0.4mm to 4mm.

As examples of possible investigation, we give now few results which have been obtained either during a rocket flight or during an Airbus A300-0g campaign.

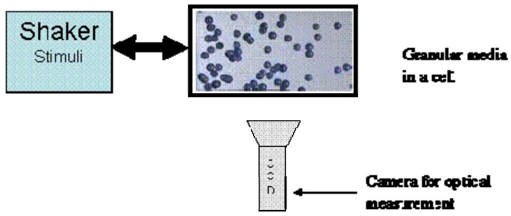

Fig. 1 typical experimental set-up. The camera shall allow 3-d diagnostic at 1000 frames/s

4. Typical behaviours obtained during rocket flight

The following results have been obtained during the Maxus 7 rocket flight, launched from Kiruna on May 2, 2006. The purpose was to study the density inhomogeneity in a granular gas excited by vibrating a cell [8-11]. So, during the flight, three cells, cf. Fig. 2, with different ball number content have been shaken and studied at the same time, using impact sensors registration and video recording: they are (i) a 3-d cell (27*9*9mm^3) containing 236 bronze spheres of 1.21mm diameter (i.e. 4.2 layers) with 3-d imaging using 2 views at right angles (they are the 2 top views of Fig.2), (ii) a 2-d cell (27*9*1.6mm^3) containing 32 bronze spheres of 1.21mm diameter (i.e. 4.2 layers), and (iii) a quasi 3-d cell (27*9*4mm^3) containing 2 bronze spheres of 1.21mm diameter to study very low density behavior and/or chaos. This one is observed at the same time as the 2-d cell, and results are superimposed; they correspond to the bottom view of **Fig.2**.

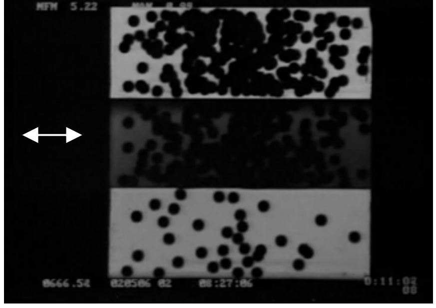

Fig. 2 top and middle cell: the 2 views at right angles of the 3d cells with 236 bronze spheres. Bottom view is the sum of a view of the 2d cell with 32 bronze spheres + the view of the 2-ball cells

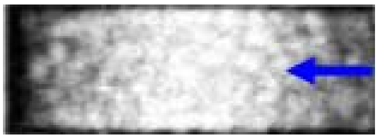

Fig. 3 a Sum over 90 photos at the same phase of the 3d cell moving backward (towards left).

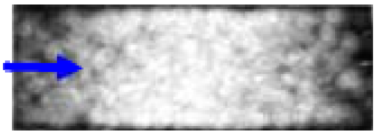

Fig. 3 b Sum over 90 photos at the same phase of the 3d cell moving forward (towards right).

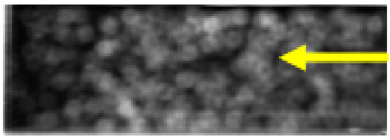

Fig. 3 c Sum over 90 photos at the same phase of the 2d cell moving backward (towards left).

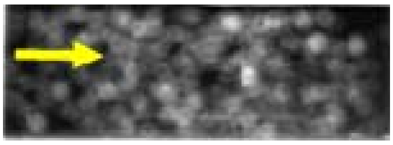

Fig. 3 d Sum over 90 photos at the same phase of the 2d cell moving forward (towards right)

Fig. 3 Maxus 7 (25Hz, 1.4mm) : Density distribution of a granular gas for the 2-d and 3-d cells filled with 3 layers of grains.

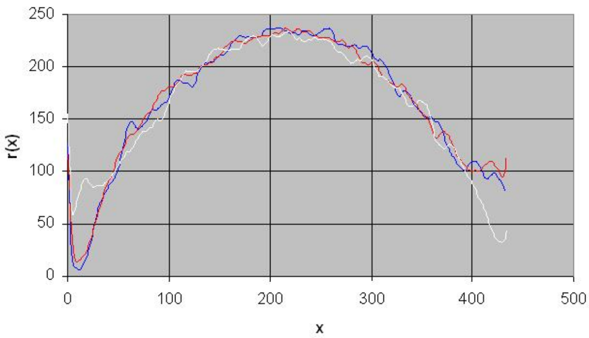

Fig. 4a density of cluster profile in the direction of vibration. Red and blue: cell moving towards negative x (the left); white: cell moving towards positive x (the right).

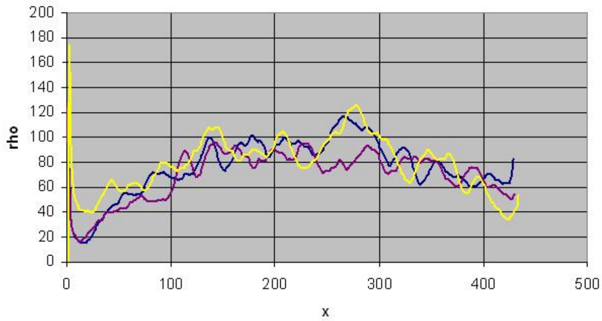

Fig. 4b density profile in 2d cell,. Blue & pink: cell moving towards negative x (the left); yellow: cell moving towards positive x (the right); x is the direction of vibration; it is in pixels with 450pixels≈29mm; rho or r(x) stand for density in a.u..

4a. Results

In Fig. 2, direction of vibration is along the larger direction of the cell. The observation through the two views at right angles allow to demonstrate that the distribution in a section perpendicular to vibration is homogeneous, and that no depletion of density is observed near the lateral ("horizontal") walls. However, a depletion is observed near the vertical walls in the perpendicular direction.

Video analysis shows that the 2 balls are not moving periodically in the cell with 2 balls. This is quite different from what has been observed previously in Airbus experiments and in Maxus 5 experiments [8]. It might be due to the increase of the cell length that increases the threshold of resonance.

In **Fig. 3**, sum of photos has been performed to determine the local density of grains at two different phases of vibration (φ=0 and π, if one writes $x=A\cos(2\pi f\, t)$).

Profiles have been determined from these sums using averaging over the width of the cell. They are reported on **Fig. 4**. The profiles are mainly regular with a maximum density at the centre and with two lateral wings. Also, the central part of the profiles does not evolve noticeably with the phase, while the most eccentric part of lateral wings does vary in opposite phase. This is true for both the 2-d cell and the 3-d one. This evolution modifies slightly the centre of mass of the cluster. The slow motion in the wings and the depletion which exists there prove that the cell moves much faster than the typical agitation speed of grains, which demonstrate in turn the supersonic kind of excitation [8), 10)]. However we can not observe shock waves. At last, we note also the similarity of the 2-d and 3-d distributions.

5. Study of g-jitter effect in Airbus experiments

To prepare the granular experiment in SJ-8 (which flew on September 2006), we have also performed tests during an Airbus A300-0g campaign on different cells and grains provided by Prof. Hou. So, two kinds of cells were used, one was similar to the one used in the Chinese satellite SJ-8 experiment (see **Fig.5**), and the other one was the one for the Maxus 7 rocket of the French-European team (see Fig.2).

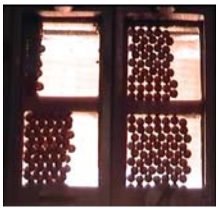

Fig. 5a: 2g,
no vibration

Fig. 5b: 2g ; vibration:
A=0.9 mm, 50Hz
$A\omega^2$=90m/s²

Fig.5c: 0g , vibration:
A=0.3 mm, 50Hz
$A\omega^2$=30m/s²

Fig.5d: 0g, vibration:
A=0.9 mm, 50Hz
$A\omega^2$=90m/s²

Fig.5e: 0g, A=0.006 mm, f= 130Hz, $A\omega^2$=4m/s²

Fig. 5 Chinese satellite cell in Airbus; gravity direction is horizontal (when it is different from 0); vibration direction is horizontal. Area fractions for the 4 cells are 43%, 56%, 78% and for the large particle in the mixture is 14%, as indicated in Fig5.e.

5a. Test of Chinese satellite cell

Concerning the Chinese satellite cell, different filling was used in each compartment, which can be measured from the cell at rest (Fig. 5a). Some preliminary conclusion is illustrated in Figure 5. One notes from comparing Figs. 5a & 5b that grains are agitated by vibration. Also, one sees from Fig.5b, that the agitated medium at 2g does not expand so much and remains closed to the "bottom wall" (i.e. to the left wall); it does not occupy the whole available space and a large free volume exists on the right part of the compartments. This is not the case for the 3 densest cells at 0g with high vibration intensity as shown in Figs. 5c & 5d, for which granular medium expends and occupies uniformly the "maximum" available space instead of remaining in a cluster, as in Fig. 5e, when either excitation is not large enough to break the cohesion, or when the gravity is playing a role as in Fig. 5b. It is to note that in Figs. 5c & 5d with large excitation in microgravity, one observes some crystalline order in the bottom-right compartment, while the system looks much more random in the top-right and bottom left compartments, as if particles could move erratically from one location to the other in these two last compartments, while they were confined in a cage in the first compartment.

We confirm this using spatial Fourier transform; it was found the persistence of a global crystalline structure in the densest cell (80% area-filling ratio) in 0g, while this order disappears in 0g in the 60% cell, proving the "liquid- or gas-like" structure.

The top-left compartment was dedicated to study binary compositions with 2 kinds of balls having different sizes. Do these particles mix easily or segregate by size? We observed localized zones of large density with large balls disperse in rather low concentration of small particles; the position of the "cluster" of large particles is found to fluctuate with time, probably sensitive to g-jitter.

Besides, we obtained the acceleration threshold needed to generate the ball vibration in preparation for the satellite experiments. More careful analyses of the data are still undergoing for further understanding of our results.

5b. Rattle effect due to g-jitter:

► *Study of the effect of g-jitter with the 2d cell of the French-European team ($L*w*h=29*9*9mm^3$)*

We have tried to study the effect of g-jitter using the 2-d sub-cell of the Maxus 7 rocket cell (cf. Fig.2). It has been found that the gas cannot be formed if g-jitter is too large and we see some erratic rattle effect. It means that the grains move as a whole from one wall to the other due to a small remaining gravity which changes of direction erratically.

On the contrary, when $v_b=A\omega$ is large enough, where A is the amplitude and $f=\omega/(2\pi)$ is the frequency of vibration, gas forms and the g-jitter becomes negligible.

A way to analyse this effect is to compute the position R=(X,Z) of the centre of mass of the gas as a function of time t and to measure its standard deviation ΔZ. If it is of the order $\Delta Z=L/2$ (L being the cell length), we see a rattle effect: the mass centre of the balls goes from one end of the cell to the opposite one. On the other hand, if ΔZ is much smaller than L then we get a "gas", whose internal "pressure" stabilises the mass centre in the middle of the cell; and the larger the "pressure" the smaller the fluctuations of ΔR. HoweverΔZ cannot be smaller than the typical fluctuations of the centre of mass of a gas containing N balls, *i.e.* $L/(2N^{1/2})$, (if one excepts cases when some electrostatics takes part). The analysis is done from the cam video.

In **Fig. 6** we present 3 different curves representing the evolution of the Z coordinate of the centre of mass as a function of time during the period of micro-gravity of 3 different parabolas. We see for one of it the rattle effect; in this case Z goes from one edge to the other. On the other hand, for the two other curves, Z remains in the vicinity of the cell centre, which corresponds to a gas-like behaviour. The difference between these two behaviours can be measured using the standard deviation ΔZ of the Z evolution. So each curve of Fig. 6 gives a single data point ΔZ. The measurement of the relative influence of g-jitter and vibration intensity is shown in **Fig. 7**, where ΔZ is plotted as a function of the vibration parameter $v_b^2=(2\pi Af)^2$, for all parabolas. As data fall on a single curve, it means that 2πAf is the right parameter. The transition from rattling to granular gas is observed; however, it is broadened since the real amplitude of g-jitter fluctuates depending on the exact condition of parabola.

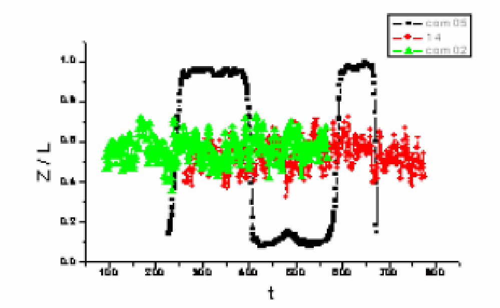

Fig. 6 Z- position of the mass centre *vs.* time t in the Maxus7 2-d cell during an Airbus parabola (green: 0.95mm,125Hz; black: 0.047mm 25Hz ; red 0.28mm 160Hz)

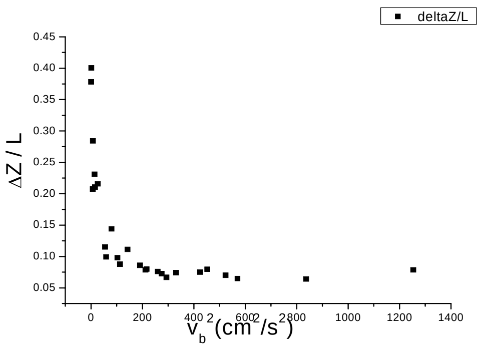

Fig. 7 ΔZ/L vs. $v_b=2\pi Af$ from Maxus-7 3d cell in A-300-0g airplane.

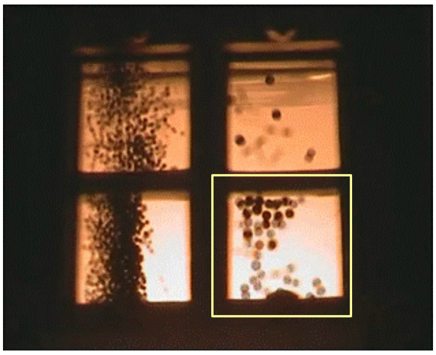

Fig. 8 Other filling used for the SJ-10 cell during an Airbus, and the sub-cell whose centre of mass has been studied during parabola .

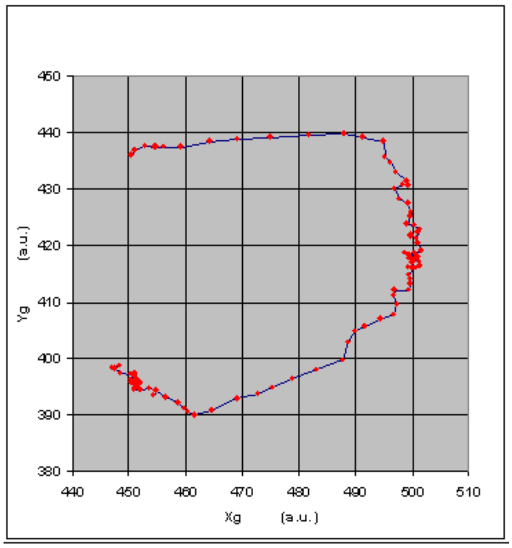

Fig. 9 Evolution of the centre of mass position of coordinates (Xg, Yg) during a parabola when excitation is small, in the case of the bottom right cell of Figure 8 .

► *Automatic measurement of the centre of mass in one of the 4 sub-cell of the satellite SJ-8 cell*

It is important to be able to treat such data automatically. This is why we have programmed an automatic procedure in Java which can be run inside the ImageJ program and which allows getting the position of the centre of mass in a cell of which we define its boundary. We could apply this procedure/macro in the case of the SJ-8 cell filled with a small number of grains. The cell for which we studied the content motion is the bottom right one in **Fig. 8**.

The result is reported in Fig. 9, where we have plotted the evolution of the centre of mass (given by its coordinate (Xg,Yg) during a parabola. Obviously, we see also the rattle effect.

6. Conclusion

Through these examples we have proved that mechanics of granular matter can be investigated in microgravity. This is a puzzling challenge, since granular matter is dangerous to handle in space environment, because grains or powders are dangerous to breathe, and because any lever/buttom can get stuck by a grain in bad position. On the other hand their manipulation is unavoidable, since they enter in most human activities. In particular, why do we need to grow plants in weightlessness condition, if we are not able to process them, to cut them in pieces or to collect and use their seeds…if.

We do not know at the moment if we can extrapolate the behaviours found on earth. However, we know that these earth behaviours are quite sensitive to details, due to the strong non linearity of the law of solid friction after some threshold. This gives to them most of their mechanical properties to granular media. Hence, we shall expect also important non linear effect in 0-g, and probably non classic behaviours too.

At the moment at least, most of the results we have obtained were predicted neither by simulations, nor by theories when addressing the statistical mechanics of a collection of grains, for which it turns out that it deviates strongly from Maxwell's….

Acknoledgements
CNES and ESA are thanked for funding, and Novespace for technical assistance.

References

1) de Coulomb C., Mémoires de mathématiques et de Physique présentés à l'Académie Royale des Sciences lus par Divers Savans et lus dans les Assemblées, (Paris: l'Imprimerie Royale) 343 (1773);
2) Faraday M.O., Philos. Trans. R. Soc. London 52, 299 (1831)
3) Beysens, D. & Evesque P., Vibrational phenomena in near-critical fluids and granular matter, In "Topical Teams in the Life & physical Sciences, Towards new research applications in space"; SP 1281, ESA publication division, co ESTEC, PO Box 299, 2200 Noordwijk, The Netherlands.
4) Kozlov V.G., Ivanova A.A. & Evesque P., sand behaviour in a cavity with incompressible liquid under vertical vibration, *Europhys. Lett.* **42**, 413-418, 2001; Evesque P., Ivanova A.A. & Kozlov V.G., Liquefaction of granular matter in viscous liquid under vertical vibration, in Powders & Grains 2001, Y. Kishino ed., 517, Balkema (Rotterdam), 2001 ; Kozlov V., Ivanova A., Evesque P. Hydrodynamical levitation of heavy solid body in cavity submitted to rotational vibrations. in Powders & Grains 97, Behringer & Jenkins ed., 421, Balkema (Rotterdam), 1997; Ivanova A.A. & Kozlov V.G., & Evesque P., *Europhys. Lett.* **35**, 159-164, 1996.
5) Louge M.Y., Xu H. & Jenkins J.T., in Powders & Grains 2001, Y. Kishino eds, 557, Balkema (Rotterdam) 2001.
6) Sture S., Batiste S.N., Lankton M., Parisi J., in *Proc. ASCE Earth and Space Conference, Engineering, Construction and Operations in Challenging Environments*, Eds. R.M. Malla and A. Maji, March 7-10, 2004, League City, Texas, pp. 78-84; see also: http://science.nasa.gov/newhome/headlines/msad27may98%5F1.htm
7) Yamanaka K., Hashimoto K., Kamehara N. & Kotani T., Powder mixing under microgravity for oxide superconductors, in Advanced Materials '93, III/A: Computations, Glassy materials, Microgravity and non-destructive Testing, T.Masumoto et al. eds, Trans. Mat.Res. Soc. Jpn, 16A, Elsevier Science, pp 681-684, 1994
8) Falcon, E., Wunenburger, R., Evesque, P., Palencia, F., Chabot, C., Fauve, S., Garrabos, Y. & Beysens, D., *Phys. Rev. Lett.* **83** 440-443, 1999.
9) Evesque, P., Palencia F., Lecoutre-Chabot C., Beysens, D. and Garrabos, Y., Microgravity Sci. technol. XVI-1, 280-284 , 2005
10) Falcon, E., Evesque, P., Palencia, F., Lecoutre-Chabot, C., Fauve, S., Beysens, D., & Garrabos, Y., *Europhys. Lett* **74**, 830, 2006
11) Evesque, P., *Poudres & Grains* **12** (4), 60-82, 2001; *ib.* **13** (2), 20-26, 2002; *ib.* **13** 40-73, 2002; *ib.* **14** (2), pp. 8-53, 2004; **15** (2), pp.18-34, 2005; ISSN 1257-3957; http://www.mssmat.ecp.fr/html_petg/rubrique.php3?id_rubrique=1