Granular Matter in Low Gravity

Erlangen, 25-27 March 2015

Dear Colleagues,

A very warm welcome to Erlangen and thank you for joining the "Granular Matter in Low Gravity"conference!

There is an increasing interest in studying granular matter, including dust, under gravity conditions different from Earth. Besides the traditional fields of astrophysical research such as cosmic dust, planetary rings, formation of planetesimals and others, low-gravity conditions provide suitable test beds to study the physics of granular matter in comparison with theoretical results, given that most of the theory of granular gases was obtained for the force-free case. Beyond these fundamental questions, on the applied side, space missions to Moon, Mars and asteroids require insight in the behavior of granular matter in low-gravity environments.

It is the aim of the meeting to provide an exciting forum to discuss the subject from different perspectives of granular-matter research such that applications benefit from fundamental insights, and applications may stimulate fundamental research.

The conference is made possible by generous support through the German Aerospace Center (DLR), the European Space Agency (ESA), and two major DFG funding initiatives: the “Engineering of Advanced Materials” Cluster of Excellence and the Collaborative Research Center for “Additive Manufacturing”. We gratefully acknowledge the support of these initiatives.

We hope you’ll enjoy the conference and your time in Franconia!

Thorsten Pöschel, *Jonathan Kollmer*, *Matthias Sperl*

Conference venue

The conference venue is the **Orangerie** of the Markgräfliches Schloss (Castle) of Erlangen next to the central Market square in Erlangen. It is within walking distance of cafés and restaurants, the central train station and a number of hotels. The street address is **Schlossgarten 1, 91054 Erlangen**.

The welcome reception on Tuesday evening will be in the 1st floor of the University Villa on the central Market square in Erlangen (**'Schloss auf dem Marktplatz'**), home to the university's central administration. It is right next to the conference venue. The street address is **Schlossplatz 4, 91054 Erlangen**.

For a map of the conference venue see the inside of the front cover.

Session Format and Talk Style

Keynote lectures: 35+10 : 35 minutes talk time plus 10 minutes discussion

Contributed talks: 15+5 : 15 minutes talk time plus 5 minutes discussion

Poster Session : Wednesday 6:30pm-10:00pm

Posters are displayed for the duration of the conference. There is a dedicated **Poster Session** on **Wednesday from 6:30pm to 10:00pm**.

Please take note of the **'People's Choice Best Poster Award'**. Your conference booklet contains a ballot slip for your choice of the three best posters. Please hand in your **completed ballot slip by Friday lunch break**. The winners will be announced at close of the last session on Friday afternoon.

Wireless Internet Access : SSID "FAU-Guest"

In the conference bag is a detailed instruction how to use the wireless network: Connect your mobile device to the network with SSID "FAU-Guest". Once connected open a webpage and you should see an input field for your credentials. **Your personalized username and password is provided in your registration bag.** Alternatively you may connect via **eduroam**.

Social events

Welcome drinks – Tuesday 6-10pm

Please join us for casual welcome drinks and snacks to kick off the conference on Tuesday 24th March from 6 to 10 pm at the university villa on the central market square.

Conference dinner – Thursday 7pm at 'Osteria la vita e bella'

You are cordially invited to our conference dinner, to be held at the 'Osteria la vita e bella' in the 'Altstädter Schießhaus' next to the site of Erlangen's famous May-beer festival 'The Berg'. The street address is **'An den Kellern 30'** which is a short 20 minutes stroll from the conference venue. The cuisine is italian with choices of pasta, pork and fish. If you have any special dietary requests please let us know. Partners, wives & husbands are very welcome if you let us know in advance.

Please bring warm clothes as we are likely to enjoy an outdoor aperitif.

Wednesday

08:45 – 09:00 Welcome

09:00 – 09:45	**Ralf Stannarius**	*Experimental studies of 3D granular gases*
09:45 – 10:05	**Peidong Yu**	*Nonlinear sound propagation in granular packings in low gravity*
10:05 – 10:25	**Robert Sütterlin**	*The soft matter dynamics platform on the International Space Station*

coffee break

11:00 – 11:45	**Nikolai Brilliantov**	*Aggregation and fragmentation kinetics in granular gases in space*
11:45 – 12:05	**Yann Grasselli**	*Translational and rotational temperatures of a 2D vibrated granular gas in microgravity*
12:05 – 12:25	**Scott Waitukaitis**	*Freely-falling granular streams: a zero-g playground for charged grain interactions*

lunch break

14:00 – 14:45	**Eric Parteli**	*Sand transport and dune formation on Mars*
14:45 – 15:05	**Meheboob Alam**	*Rarefaction phenomena in plane Poiseuille flow of a granular gas*
15:05 – 15:25	**Eric Clement**	*Sound propagation in granular packing: the quest for ultra-low confining pressure*

coffee break

16:00 – 16:45	**Diego Maza**	*Symmetry beaking and granular flows in low gravity*
16:45 – 17:05	**Matthias Schröter**	*Floating in a jam: granular packings at low gravity*
17:05 – 17:25	**Dan Serero**	*Sedimentation and collapse of a granular gas under gravity*

short break

17:45 – 18:30	**Klaus Dieter Relotius**	*Experiments at ISS – Metal Additive Layer Manufacturing In Space (MALMIS)*

18:30-22:00 Poster Session & Finger Food

Keynote **Ralf Stannarius** **09:00 – 09:45**

Experimental studies of 3D granular gases

Ralf Stannarius* and Kirsten Harth

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Among the manifestations of granular materials that are encountered in everyday life, granular gases represent very peculiar systems: they are dilute ensembles of macroscopic grains, interacting by inelastic collisions. Permanent energy mechanical supply is required to maintain a dynamic steady state. Otherwise the kinetic particle energy is gradually dissipated, the gas is 'cooling'. Concepts like granular temperature are adopted from equilibrium thermodynamics of molecular systems, but one has to bear in mind that granular gases in fact represent non-equilibrium systems. Numerous theoretical studies can be found in the literature that deal with simulations of this apparently simple non-equilibrium dynamical system. Experiments have mainly been conducted in 2D geometries and/or with small ensemble sizes. Frequent interactions with the container walls influence the measured statistics significantly. The excitation schemes can create artifacts.

Real three-dimensional ensembles of granular gases under weak excitation can only be studied in micro-gravity. A pioneering experiment with spherical grains was performed by Falcon et al. already 1999 [1]. While this early study did not yield quantitative statistical data on the particle level, it produced a valuable demonstration of dynamical clustering and helped to identify problems with excitation and observation techniques.

Recently, the first particle-based quantitative analysis of a 3D granular gas was published [2]. In ensembles of rod-like grains, new studies under permanent excitation as well as granular cooling experiments have been performed, and quantitative information on velocity distribution functions, the validity of the equipartition theorem for kinetic energies and cooling dynamics are available.

Progress in this field is reviewed, and results of the statistical characterization of granular gases in 3D experiments are discussed. An outlook to future experimental perspectives is given.

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Snapshot of rods of 15 mm length in a drop tower 'cooling' experiment. The side walls are vibrated for about 1 sec at the beginning of the microgravity phase, then excitation is stopped and the dissipation of kinetic energy is monitored.

ACKNOWLEDGMENTS

Torsten Trittel, Sandra Wegner and Kathrin May are acknowledged for valuable contributions to experiments. The project was funded by the German Aeropace Center (grants 50WM1241 and 50WB1344) and DFG within grant STA-425/34.

[1] E. Falcon, R. Wunenburger, P. Evesque, S. Fauve, C. Chabot, Y. Garrabos, and D. Beysens, Phys. Rev. Lett., **83**, 440 (1999). E. Falcon, S. Aumaitre, P. Evesque, F. Palencia, C. Lecoutre-Chabot, S. Fauve, D. Beysens, and Y. Garrabos, Europhys. Lett., **74**, 830 (2006).
[2] K. Harth, U. Kornek, T. Trittel, U. Strachauer, S. Höme, K. Will, and R. Stannarius, Phys. Rev. Lett., **110**,144102 (2013).
[3] K. Harth, T. Trittel, U. Kornek, S. Höme, K. Will, U. Strachauer, and R. Stannarius, AIP Conf. Proc. (Powders and Grains), **1542**, 807 (2013).

Peidong Yu **09:45 – 10:05**

Nonlinear Sound Propagation in Granular Packings in Low Gravity

Peidong Yu* and Matthias Sperl

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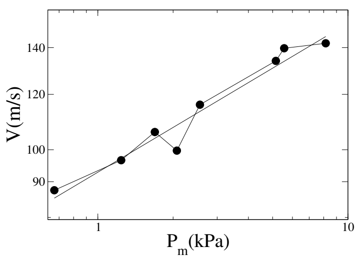
Sound propagation in granular packings is known to exhibit nonlinear behavior [1], due to disordered particle positions, nonlinear contact forces between particles, and inhomogeneous elastic properties of the packings. This nonlinear behavior becomes even more prominent when reducing the confining pressure of a tight packing and approaching the jamming point. Simulations [2] and experiments on ground [3, 4] have been performed in this regime, the most important result of which is a changing speed of sound V_s with a changing sound magnitude P_m (c.f. [3], Fig. 3), a clear signal of shock-wave-like nonlinear sound propgations. However, experiments in the lab cannot avoid the confining pressure induced by particle weights.

We develop an automated sound measurement device and implement it into a droptower capsule. With the low gravity condition provided by the droptower, we are able to remove the pressure induced by the particles themselves and reach an even more nonlinear regime for the sound propagation. The change of V_s versus P_m is measured (Fig. 2) and the results are compared with those from the ground experiment.



Speed of sound versus sound magnitude in low gravity.

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[1] C. Liu and S. R. Nagel, Phys. Rev. Lett. **68**, 2301 (1992).
[2] L. R. Gomez, A. M. Turner, M. van Hecke, and V. Vitelli, Phys. Rev. Lett. **108**, 058001 (2012).
[3] S. van den Wildenburg, R. van Loo, and M. van Hecke, Phys. Rev. Lett. **111**, 218003 (2013).
[4] S. van den Wildenburg, M. van Hecke, and X. Jia, Euro. Phys. Lett. **101**, 14004 (2014).

Robert Suetterlin **10:05 – 10:25**

The Soft Matter Dynamics Platform on the International Space Station

Robert Sütterlin*

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> There is an increasing interest in studying granular matter[. . .] low-gravity conditions provide suitable test beds to study the physics of granular matter in comparison with theoretical results, given that most of the theory of granular gases was obtained for the force-free case.

The European Space Agency has recently contracted the manufacturing of the Soft Matter Dynamics platform. An experiment container for the Fluid Science Laboratory in the Columbus Module of the International Space Station. The Soft Matter Dynamics platform is an open design that allows the investigation of the dynamics of macroscopic condensed matter applying high resolution camera and light scattering diagnostics. Originally the Soft Matter Dynamics platform was aimed at the study of the coarsening of wet foams under microgravity [1]. Yet ESA anticipated the interest in similar investigations with other soft matter, namely dense granular matter [2] and particle laden emulsions [3]. But application and utilization of the platform needs not end here.

Airbus Defence and Space has implemented a fully functional elegant bread board of the Soft Matter Dynamics platform and realized experiment specific inserts for investigations of coarsening of wet foams (FOAM-C) as well as dynamics in compact granular matter (CompGran). During the 56th ESA parabolic flight campaign the design was validated, and preliminary science tests were conducted for FOAM-C and CompGran. The Soft Matter Dynamics elegant bread board could demonstrate the generation of homogeneous wet foams under micro-gravity conditions. A total of four design alternatives for implementing a CompGran experiment insert were tested and evaluated during the PFC and the most reliable design has been identified.

The Soft Matter Dynamics platform is designed to allow continous measurements under stable conditions for hours and possibly days to fully exploit the

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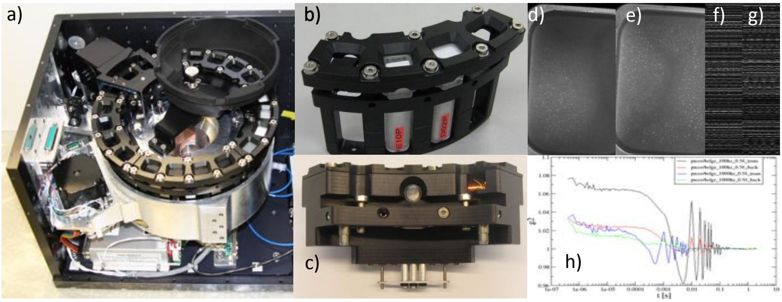

The Soft Matter Dynamics elegant bread board (a), FOAM (b) and CompGran (c) experiment inserts. Foam generated under μg with a watery solution of TTAB 5g/L 5% (d) and 15% (e). The dynamics of granular matter have been assessed using the SVS / TRC based on line camera recordings (f and g). The fundamental frequencies of the piezo agitation can be clearly identified in the DWS measurements (h).

extended micro-gravity periods available on the International Space Station. Also measurements at short time scales and over short periods of time are possible. This can be used to identify single events, study transient phenomena and to support extremely long time investigations like for instance the transitions to glassy dynamics.

ACKNOWLEDGMENTS

The author would like to thank ESA for their trust in the capabilities of Airbus DS to build such a great tool for science. Also I would like to express my gratitude to the science team of the Soft Matter Dynamics platform for the energy and enthusiasm they invest in this research.

[1] AO-1999-108 Hydrodynamics of Wet Foams (FOAM)
[2] AO-2009-943 Compaction and Sound Transmission in Dense Granular Media (CompGran)
[3] AO-2009-0813 PArticle STAbilised Emulsions and Foams (PASTA)

Keynote **Nikolai Brilliantov** **11:00 – 11:45**

Aggregation and fragmentation kinetics in granular gases in space

Nikolay Brilliantov*

Department of Mathematics, University of Leicester, Leicester, UK

Simple models of ballistic aggregation and fragmentation are studied. The models are characterized by two energy thresholds, $E_{\rm agg}$ and $E_{\rm frag}$, which demarcate collisions with different outcome – aggregation, rebound or fragmentation. We analyze different fragmentation models, including the model of complete decomposition into monomers and fragmentation with a power-law debris size-distribution. We start from Enskog-Boltzmann equation for the mass-velocity distribution function and derive Smoluchowski-like equations for concentrations of particles of different mass. We analyze these equations analytically and numerically. In particular we show that the resulting steady-state distribution of particles in the systems where a balance between aggregation and fragmentation is sustained is not sensitive to particular form of the size distribution of debris, provided that it is steep enough. Application to the Saturn Rings is considered.

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Yann Grasselli **11:45 – 12:05**

Translational and rotational temperatures of a 2D vibrated granular gas in microgravity

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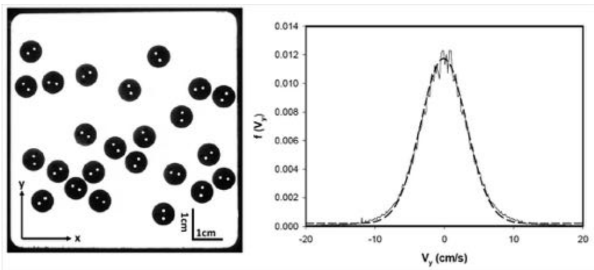
We present an experimental study performed on a vibrated granular gas enclosed into a 2D rectangular cell. The particles are made of brass disks enclosed in a rectangular cell and the area fractions used are 8.3% and 16.6%. Experiments are performed in microgravity conditions achieved during parabolic flights. The cell is submitted to an external periodic vibration. The disks are pierced with two holes and the observations are realized through transmission. This allow to identify the angular orientation of the disks during the experimental investigation. High speed video recording and optical tracking allow to obtain the full kinematics (translation and rotation) of the particles. The inelastic parameters are retrieved from the experimental trajectories as well as the translational and rotational velocity distributions.



Left picture: typical raw experimental picture recorded during the period of microgravity in the presence of the external vibration (along the y-direction). The two holes, used for the optical tracking of the particles, can be clearly identified. Right picture: velocity distribution of particles along the direction of the vibration.

It clearly appears that the cell can be divided into 3 different regions: two hot ones (at the top and bottom) where energy in injected into the medium and a cold one at the center of the cell where the behavior of the medium is mainly governed by particle-particle interactions [1]. We report that the experimental

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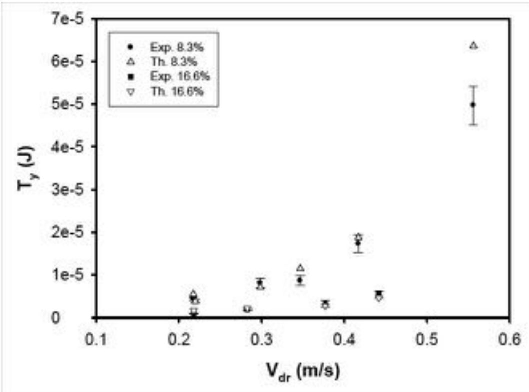
ratio of translational T_{tr} versus rotational T_{rot} temperature decreases with the density of the medium but increases with the driving velocity of the cell. These experimental results are compared with existing theories and we point out the differences observed [2]. A model, based on a balance between the injected and dissipated energy, is presented and fairly predicts the equilibrium experimental temperatures along the direction of vibration [3,4].



Comparison of the equilibrium temperature as a function of the driving velocity of the cell V_{dr}.

ACKNOWLEDGMENTS

We would like to thank the NOVESPACE and the CNES for giving us the possibility to board the A300-zero G in order to perform our experiments.

[1] R. Soto, Phys. Rev. E, **69**, 061305 (2004)
[2] O. Herbst, R. Cafiero, A. Zippelius, H. J. Herrmann and S. Luding, Phys. Fluids, **17**, 107102 (2005)
[3] E. Falcon, J.-C. Bacri and C. Laroche, Powders and Grains 2013, **1542**, 815 (2013)
[4] N. Rivas, S. Luding and A.R. Thornton, New J. of Phys., **15**, 113043 (2013)

Scott Waitukaitis **12:05 – 12:25**

Freely-falling granular streams: a zero-g playground for charged grain interactions

Scott Waitukaitis,[1,*] Victor Lee,[2,3] and Heinrich Jaeger[2,3]

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In everyday situations involving granular media, gravity is by far the dominant force [1]. Even so, other forces are present, and in the absence of gravity these can lead to dramatically different phenomena of fundamental importance [2]. Observing freely-falling granular streams with a co-falling high-speed camera, we characterize and quantify electrostatic interactions between individual, microscopic grains [3]. The zoology of behaviors includes attractive orbits and repulsive slingshot events, cluster growth via molecule formation, and cluster annihilation via high-speed impact [4]. Using orbital paths, we estimate charges for pairs of particles by fitting; alternatively we also measure the ensemble charge distribution via acceleration by a uniform external electric field [5]. We observe firsthand the important role of particle polarization, especially in molecule formation. These results have important implications in contexts ranging from the origin of same-material tribocharging [3] to the agglomeration of protoplanetary dust [6, 7].

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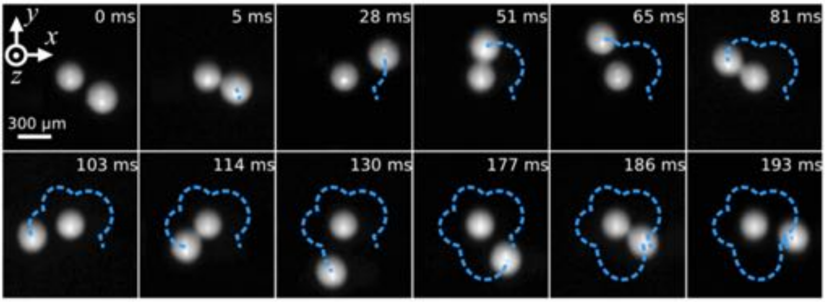

Time series images of charged ~300 μm zirconium-silicate grains undergoing attractive, elliptical orbit segments interrupted by inelastic collision events. The reference frame is fixed on the center of the somewhat smaller particle while the path of the larger particle is traced out. The charge scale of each grain is on the order of ~1 million electrons, as confirmed by fitting the orbits and consistent with separate uniform field experiments.

ACKNOWLEDGMENTS

This research was supported by NSF through DMR-1309611. S.R.W. acknowledges support from a University of Chicago Millikan Fellowship and from Mrs. Joan Winstein through the Winstein Prize for Instrumentation. The Chicago MRSEC is gratefully acknowledged for access to its shared experimental facilities.

[1] H. Jaeger, S. Nagel, and B. Behringer, Rev. Mod. Phys. **68**, 1259 (1996).
[2] J. Royer *et al.*, Nature **459**, 1110-1113 (2009).
[3] S. Waitukaitis, V. Lee, J. Pierson, J. Forman and H. Jaeger, Phys. Rev. Lett. **112**, 218001 (2014).
[4] V. Lee, S. Waitukaitis, M. Miskin and H. Jaeger, *in preparation.*
[5] S. Waitukaitis and H. Jaeger, Rev. Sci. Instr. **84**, 025104 (2013).
[6] T. Poppe, J. Blum, T. Henning, Astrophys. J. **533**, 472-480 (2000).
[7] J. Blum and G. Wurm, Annu. Rev. Astron. Astr. **46**, 21-56 (2008).

Keynote **Eric Parteli** **14:00 – 14:45**

Sand transport and dune formation on Mars

Eric J. R. Parteli*

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The transport of sand by wind is a major agent shaping the surface of today's Mars. The formation and migration of Martian dunes is amongst the most studied phenomena resulting from wind-blown sand on the red planet, because the morphodynamics of these dunes may provide excellent proxy for Martian wind regimes and attributes of sediment. However, it is important to understand the characteristics of wind-blown sand under the lower gravity of Mars and an atmospheric density that is almost 100 times lower than the Earth's.

This talk presents insights into the characteristics of sand transport and wind regimes on Mars gained from numerical simulations using a morphodynamic model for dunes [1]. The dune model combines an analytical description of the average turbulent wind field over the topography with a continuum model for *saltation* — which consists of sand grains moving downwind close to the ground in nearly ballistic trajectories thereby ejecting new grains upon collision with the sand bed. This model reproduces quantitatively the shape of terrestrial dunes, as well as measured sand flux and wind velocity profiles over them. Here we apply the dune model to calculate dune formation under conditions valid for Mars.

The first Martian dune shape we investigate is the barchan (Fig. 7a), which is a common dune shape in many Martian craters, as well as on coastal and desert areas of the Earth. The barchan forms when the wind blows approximately all time from the same direction. It displays two limbs pointing in the dune migration trend and a slip face between these limbs, which serves as sand trap and is the side of the dune where sand is transported downhill through avalanches [3]. Martian barchans are typically 10 times bigger than the Earth's and have a more elongated shape compared to their terrestrial counterparts. Based on the size and shape of Martian barchans, we obtain insights into the characteristics of wind-blown sand on Mars from the results of our numerical simulations. Specifically, we find that the efficiency of the grain-bed collisions (splash) in entraining grains into saltation is much higher on Mars than it is on Earth, and that Martian intra-crater barchans are formed by wind speeds close to the minimal threshold for sand transport.

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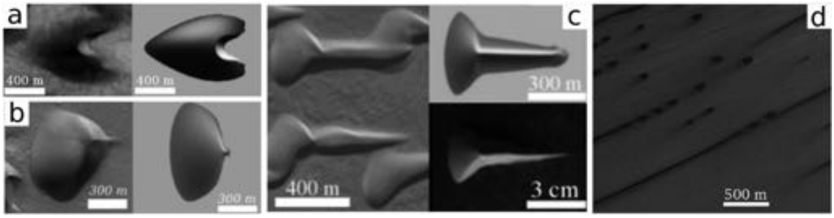

(a) Barchan dunes at Martian Arkhangelsky crater (left: image; right: simulation); (b) wedge dunes at Wirtz crater (left: image; right: simulation); (c) wedged dunes with a straight tail in Noachis Terra (left: image; right: simulation (top) and flume experiment [5] (bottom)); (d) image of dunes at Chasma Boreale, Martian north polar region. Images credit: NASA/JPL/MSSS.

Moreover, we find that unusual dune shapes occurring on Mars form when the wind alternates between two main directions, and when the availability of mobile sand on the ground is low [2, 4]. Some of these dunes have a wedged shape (Fig. 7b), others display a straight tail that elongates in the resultant transport trend as we can see in Fig. 7c. Flume experiments [5] performed with the same flow conditions as in our simulations obtained similar dune shapes thus confirming that bimodal sand-moving flow regimes and low sand availability are the main conditions for these dunes to emerge.

However, the dunes of the north polar region known as Chasma Boreale on Mars present a long-lasting puzzle. In this region, domes and unusual rounded barchans displaying an ellipsoidal shape occur side-by-side with straight linear dunes (Fig. 7d). If these straight dunes were formed by changing wind directions, then the barchans shouldn't be there. On the contrary, the straight dunes simply couldn't exist at Chasma Boreale if sand-moving winds there were unidirectional, because longitudinal dunes are unstable under unidirectional flows and decay into a chain of barchans [1, 5]. To solve this puzzle, it has been suggested that the Chasma Boreale dunes are indurated due to sand cementation by ice or mineral salts. However, how the mechanism of sand cementation could contribute to shape the Chasma Boreale dunes is still uncertain. Some insights gained from numerical simulations [3] will be presented.

ACKNOWLEDGMENTS

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Centre (JSC).

[1] E. J. R. Parteli, K. Kroy, H. Tsoar, J. S. Andrade Jr., and T. Pöschel, Eur. Phys. J. Spec. Top. **223**, 2269 (2014).
[2] E. J. R. Parteli, O. Durán, M. C. Bourke, H. Tsoar, T. Pöschel, and H. J. Herrmann, Aeolian Res. **12**, 121 (2014).
[3] A. D. Araújo, E. J. R. Parteli, T. Pöschel, J. S. Andrade Jr. and H. J. Herrmann, Sci. Rep. **3**, 2858 (2013).
[4] E. J. R. Parteli, M. P. Almeida, O. Durán, J. S. Andrade Jr., and H. J. Herrmann, Comp. Phys. Comm. **180**, 609 (2009).
[5] E. Reffet, S. Courrech du Pont, P. Hersen, and S. Douady, Geology **38**, 491 (2010).

Meheboob Alam **14:45 – 15:05**

Rarefaction phenomena in plane Poiseuille flow of a granular gas

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Two well-known rarefaction phenomena [1], the *Knudsen minimum effect* and the *bimodality* of the temperature profile, are investigated in granular Poiseuille flow via event-driven simulations of smooth inelastic hard-disks under gravity in the dilute limit. We show that the Knudsen minimum is absent in granular Poiseuille flow even for quasi-elastic collisions ($e_n \leq 0.99$), irrespective of wall conditions. In the elastic limit ($e_n \to 1$) with ultra-smooth walls (i.e. most of the particle-wall collisions are characterized by reflected-type collisions and the remaining small fraction being of diffuse type [2]), we find a local minimum in the flow rate that occurs at a Knudsen number of $Kn \sim O(0.01)$; the maximum flow rate in this case occurs at a finite Knudsen number of $Kn \sim O(1)$ in contrast to the well-known result of the maximum flow rate at $Kn = 0$. The order-one value of the first normal stress difference at $e_n \neq 1$ is responsible for the accelerated flow with increasing dissipation and that also seems to be a key for the absence of Knudsen minimum in granular Poiseuille flow.

The bimodal-shape of the temperature profile, with a minimum at the channel centerline and two symmetric maxima away from center, is demonstrated to exist in dilute granular Poiseuille flow. The origin of temperature bimodality is tied to finite Kn-effects since the underlying NSF-equations predict a temperature maximum at the channel centerline. Increasing inelastic dissipation increases the excess temperature ratio ΔT which implies that the degree of temperature bimodality is enhanced by dissipation. Furthermore, the transverse location of temperature maxima (scaled by the centerline mean free path) remains nearly constant with decreasing en for a range of e_n , but increases sharply beyond a critical value of $e_n \sim 0.3$. The latter result is shown to be tied to dissipation-induced clustering of particles wherein the flow undergoes a transition from a plug-type to slug-type flow. A quantitative comparsion of simulation data is made with the predictions of a kinetic model [3]. Our results on various characteristic features of temperature bimodality differ quantitatively (and qualitatively in some cases) from the above theory.

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[1] M. Alam and D. Shivanna, A. Mahajan, Preprint (2015, soon to be submitted)
[2] M. Alam, V. Chikkadi, J. Fluid Mech., **653**, 175-219 (2010).
[3] M. Tij, A. Santos, J. Stat. Phys., **117**, 901-928 (2004).

Eric Clement **15:05 – 15:25**

Sound propagation in granular packing: the quest for ultra-low confining pressure

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The mechanical status of a granular packing under low confining pressure is an open and controversial question with many contradictory results both from theoretical and also experimental points of view. The granular aspect of contact law implies a non-linear relation between force (F) and displacement (δ) called Hertz-law: $F \propto E_0(\delta/d)^{3/2}$, where E_0 is the bulk elastic modulus and d a typical grain diameter that can viewed, more generally, as an effective radius of curvature describing the contact between the two solid surfaces. The immediate outcome of this relation is a scaling relation between sound velocity c and confining pressure P as: $c \propto c_0(\phi Z)^{1/3}(P/E_0)^{1/6}$, where c_0 is the material bulk velocity, ϕ the packing fraction and Z the mean number of contact/grain. This last relation is often called the "mean-field" sound velocity relation, as the granular packing structure is represented via two simple parameters ϕ and Z stemming theoretically from a strong approximation that microscopic and macroscopic granular displacements remain affine. This last hypothesis simplifies tremendously the analytical computations, however it can hardly be sustained in reality. Numerical simulations of elastic response of sphere packing have shown precisely the breaking of such a mean-field approximation (see for example Makse et al.[1] and refs inside). Experimentally, the mean-field relation is only recovered for very high pressure confinement (10^8 Pa for packing of glass spheres) but for lower pressure (around 10^6 in this last reference system) the mean-field relation clearly does not hold [2]. A claim of a scaling relation $c \propto P^{1/4}$ was made instead (see Jia et al. [2] and refs inside), which seems to agree with theoretical claims coming from very different conceptual standpoints: (i) the status of granular contacts (angular shape [3] or soft shell geometry [4]) or (ii) the existence of a zig-zag buckling instability affecting the force chains transmitting sound [3]. In the recent years, our visions of granular packing was deeply affected by the many theoretical studies around the jamming transition viewed as a rigidity transition for granular packing displaying a critical point at a critical number of contacts per grain Z_c [5]. Indeed, the existence of a critical

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point would affect the elastic moduli, in particular the shear modulus, inducing a dependence of the sound velocity under uniaxial compression as $c \propto P^{1/3}$. Yet another exponent! To reach the limit of low confining pressure where the elastic anomaly should be revealed, surface sound wave propagation experiments were performed by different groups, which gave totally contradictory results [6, 7] and so far, no clear vision of the mechanical status of granular packing under weak confinement has been reached!In the recent years, our visions of granular packing was deeply affected by the many theoretical studies around the jamming transition viewed as a rigidity transition for granular packing displaying a critical point at a critical number of contacts per grain Z_c [5]. Indeed, the existence of a critical point would affect the elastic moduli, in particular the shear modulus, inducing a dependence of the sound velocity under uniaxial compression as $c \propto P^{1/3}$. To reach the limit of low confining pressure, surface sound wave propagation experiments were performed by different groups [6, 7], which gave totally contradictory results and so far, no clear vision of the mechanical status of granular packing under weak confinement was reached! To try to clarify this question, we used the parabolic Zero-G flight facility provided by Novespace in Merignac. In absence of gravity the confining pressure can be fixed in principle at very low values without the limitation of hydrostatic pressure. However, one has to keep in mind that for real zero-G flight conditions, there is always a pressure modulation due to a remnant G-jitter of about $\pm 5.010^{-3}g$. In two CNES parabolic flight campaigns (March/October 2014), we performed acoustic propagation studies on a granular packing of glass beads. We used a cell where the confining pressure was maintained by a feedback loop such as to insure a fixed confinement at the level of the pistons producing the acoustic wave. We validated our experimental method and for the first time, wave speed measurements were obtained at pressures as low as a few hundreds of Pascals. For the moment it is not possible to discriminate between the different models, except to exclude the mean field vision. Subsequently, we want to lower the confining pressures of at least one order of magnitude.

ACKNOWLEDGMENTS

We acknowledge the Novespace team in Bordeaux for many advices and help around the zero-g experimental set-up and also the financial support of the CNES.

[1] H. A. Makse, N. Gland, D. L. Johnson, and L. M. Schwartz Phys. Rev.E **70**, 061302 (2004).
[2] X. Jia, C. Caroli, and B. Velicky, Phys. Rev. Lett. **82**, 1863(1999).
[3] J. D. Goddard, Proc. R. Soc. London A **430**, 105 (1990)
[4] P.-G. Gennes, Europhys. Lett. **35**, 145 (1996)
[5] M van Hecke , J. Phys.: Cond. Matt. **22** 033101 (2010).
[6] L. Bonneau, B. Andreotti, and E. Clement, Phys. Rev. Lett. **101**, 118001 (2008)
[7] X. Jacob et al., Phys. Rev. Lett. **100**, 158003 (2008).

Keynote **Diego Maza** **16:00 – 16:45**

Symetry beaking and granular flows in low gravity

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Here we summarize some preliminary results related with the possibility of observing collective macroscopic motions when a granular sample is subjected to external perturbations , like vibrations or Couette-like shear stress, and under strong confining conditions

In the first case, collective motion appears when a granular sample is shaken from below under the gravity action, and the resulting structures depend on the lateral dimension of the confining. Indeed, shallow layers of particles display beautiful spatial order [1] but deep layers describe global collective movements similar to the observed in small aspect ratio thermal convective systems [2]. The small aspect ratio condition imply layers where the lateral dimension is comparable to the height of the container and under this condition, the role of factors like air lubrication or wall friction is still controversial. On the contrary, Couette-like driving is probably the most common geometry used to characterize granular flows and where a exhaustive number of studies have been performed linking microscopic interaction and macroscopic fields.

Both situations have recently been tested on micro-gravity conditions. In the former case [4] the experimental evidence indicates that collective movements like radial flows disappear under low gravity conditions. Moreover, similar arguments can be applied to the convection dynamics in agitated systems as we observed in parabolic flight tests [5].

In this work we study the possibility of recovering convective movements in microgravity conditions by "breakingßome of the symmetries present in the systems. For shacken systems we implement an asymmetric container, where the "top"wall was replaced by a conical lid. Under this condition, radial momentum transfer can be induced and indeed, preliminary experimental analysis suggests the existence of a toroidal convective state. Unfortunately, g-jitter effects present in parabolic flights are sufficiently strong to induce similar dynamics and more experimental efforts are necessary to test the validity of our observations. In addition, we test numerically the same idea in a Couette geometry by breaking the

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symmetry of the systems introducing different particle-wall interactions at both boundaries and very preliminary results suggest the development of macroscopic collective motions.

ACKNOWLEDGMENTS

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[1] F. Melo, P.B. Umbanhowar, H.L. Swinney. Phys. Rev. Lett **75** 3838, (1995).
[2] A. Garcimartín, D. Maza, JL. Ilquimiche, I. Zuriguel. Phys. Rev. E **65** 031303 (2002).
JM. Pastor, D. Maza, I. Zuriguel, A. Garcimartín, JF. Boudet. Physica D **232** 128 (2007).
[3] MiDi, GDR, European Phys. Jour. E **14** 341 (2004).
[4] N. Murdoch, B. Rozitis, K. Nordstrom, S.F. Green, P. Mechel, T.-L. de Lophem and W. Losert. Phys. Rev. Lett. **110**, 018307 (20013).
[5] VipGran Topical Team, ESA. 47th ESA Parabolic flight campaing, 11-21 December (2007).

Matthias Schröter 16:45 – 17:05

Floating in a jam: granular packings at low gravity

Matthias Schröter,[1, *] Jean-François Métayer,[1] Sibylle Nägle,[1] Melissa Jerkins,[2] Donald Suntrup,[2] Harry Swinney,[2] Charles Radin,[3] Tomaso Aste,[4] Mohammad Saadatfar,[4] and Tim Senden[4]

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The role of gravity in granular packings is two-fold. First, due to its vector nature it breaks the spatial symmetry which might result in anisotropies created during preparation of the packing. Second, as a volume force it provides an interparticle pressure which will saturate in the presence of boundaries [1, 2]. Both aspects can be controlled by preparing the packing inside a liquid with a material density approaching the density of the granular medium. Figure 63 demonstrates that this techniques allows to determine the volume fraction where a packing gains for the first time mechanical stability, the so called Random Loose Packing [3–5]. At finite material density differences between liquid and granular media, corresponding to reduced but still finite gravity, the volume fraction ϕ of the sample can be tuned over the full range accessible for amorphous packings. This allows to measure mechanical properties such as the penetration force or yield stress as a function of ϕ and over a large range of strain rates [6, 7].

[1] L. Vanel and E. Clément, Eur. Phys. J. B **11**, 525 (1999).
[2] M. Sperl, Gran. Mat. **8**, 59 (2006)
[3] K.J. Dong, R.Y. Yang, R.P. Zou, and A.B. Yu, Phys. Rev. Lett. **96**, 145505 (2006).
[4] M. Jerkins, M. Schröter, H. L. Swinney, T. J. Senden, M. Saadatfar, and T. Aste, Phys. Rev. Lett. **101**, 018301 (2008).
[5] G.R. Farrell, K. M. Martini, and N. Menon, Soft Matter **6**, 2925 (2010)
[6] M. Schröter, S. Nägle, C. Radin, and H. L. Swinney, Europhys. Lett. **78**, 44004 (2007).
[7] J.-F. Métayer, D. J. Suntrup III, C. Radin, H. L. Swinney, and M. Schröter, Europhys. Lett. **93**, 64003 (2011).

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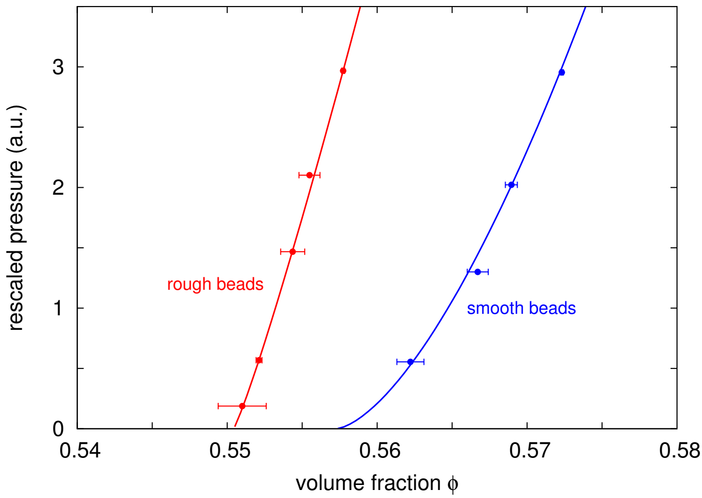

Random Loose Packing, the lower limit of mechanically stability in packings, depends on both the friction coefficient (here 0.45 and 0.53) and pressure. The latter is due to gravity; it can be controlled using liquids of different densities. Data modified from [4].

Dan Serero **17:05 – 17:25**

Sedimentation and Collapse of a Granular Gas under Gravity

Dan Serero,[1,*] Lidia Almazán,[1] Clara Salueña,[2] and Thorsten Pöschel[1]

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A granular gas, i.e a collection of particles interacting by inelastic collisions, needs external supply of energy in order to persist under gravity, due to its inherent dissipative nature. Without this energy input, such a system rapidly come to rest in the form of a dense granular packing. A hydrodynamic study of such a gravity driven transition is presented: Employing a high-order, shock-capturing numerical scheme to solve the pertaining hydrodynamic equations, we analyse the gravity driven sedimentation of a system of inelastic hard disks initially heated from below, after energy supply is switched off. Our study reveals that the process exhibits a complex behavior, characterized by cycles of diffusive and inertial regimes. Self organized shocks appear, materialized by the propagation of fronts separating between subsonic and supersonic behavior accompanied by steep temperature profiles. The late stages of the collapse exhibit a scaling regime in accordance with recent experimental findings.

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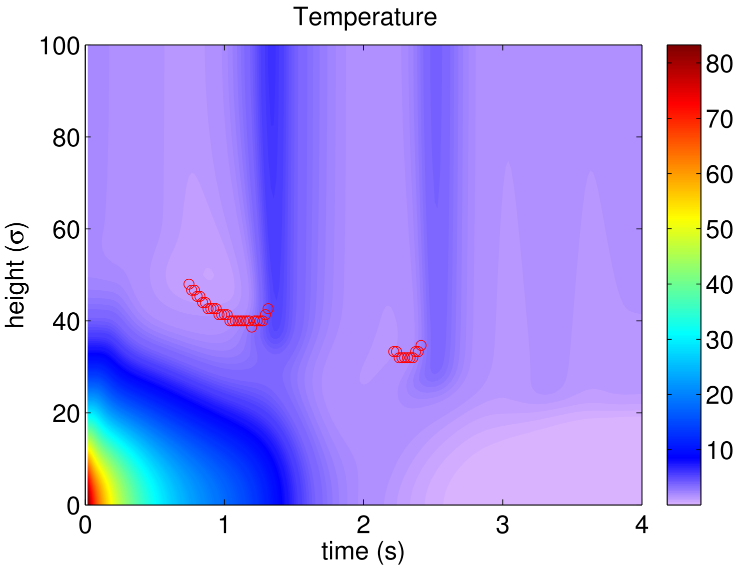

Evolution of the temperature of a sedimentating granular gas. Circles represent the front separating between subsonic and supersonic areas

Keynote **Klaus-Dieter Relotius** **17:45 – 18:30**

Experiments at ISS – Metal Additive Layer Manufacturing In Space (MALMIS)

Klaus-Dieter Relotius* and Stefan Petschelt

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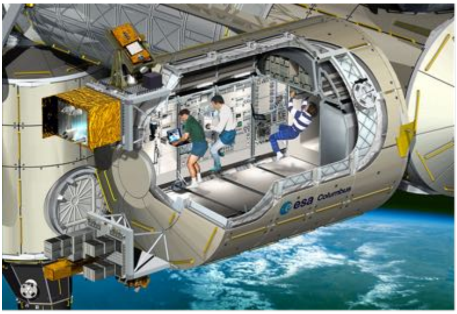
Since 2008 the European Laboratory Module COLUMBUS is attached to the International Space Station ISS. COLUMBUS allows flexible execution of experiments of different disciplines. The baseline configuration of ESA consists of 4 experiment racks for biological, fluid and physiological experiments. One rack provides the housing for experiments in standard ISS drawers with interfaces for power, telemetry and telecomand, water cooling, vacuum and waste gas (see Fig. 63).



European Laboratory Module COLUMBUS.

In the past several experiments were developed and implemented in a time frame from 2.5 to 5 years. The science community requested a faster approach. In the frame of the DLR experiment Magnetic Flow Experiment MFX/MagVector during the BLUE DOT mission 2014 it was demonstrated that a development within 15 month is possible for an ISS drawer based experiment (see Fig. 64).

Based on this experience a family of experiment boxes with standard COLUMBUS interfaces, so called class 3 payloads, were developed. These can be easily adapted to the experiment needs and ensure a short development time. They

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MFX/MagVector experiment.

enable the operation of the experiment from national User Support Operation Centre or from experimenter sides. As example for a future implementation of a class 3 payload the development of a 3D-printer for metal is added. AIRBUS Defence&Space started the project Metal Additive Layer Manufacturing In Space -MALMIS- to develope a technology which can be applied in space. The presentation provides an overview about first results and an outlook of further development which shall end up in a 3D-printer for metal in ISS.

Thursday

09:00 – 09:45	**Meiying Hou**	*Experimental study of granular dynamics in microgravity*
09:45 – 10:05	**Caroline de Beule**	*Blowfish: An insolation activated dust layer*
10:05 – 10:25	**Ralph Lorenz**	*Bedforms in a thick atmosphere, low gravity environment - Titan*

coffee break

11:00 – 11:45	**Philip Metzger**	*Low gravity granular physics: a key to the future of humanity*
11:45 – 12:05	**Paul Sanchez**	*Rotational disruption of self-gravitating granular aggregates*
12:05 – 12:25	**Ingo von Borstel**	*The Brazil Nut effect under varying gravitation and excitation*

lunch break

14:00 – 14:45	**Mihaly Horanyi**	*Characterizing the lunar regolith by laboratory and space experiments*
14:45 – 15:05	**Achim Sack**	*Granular dampers in microgravity*
15:05 – 15:25	**Eric Opsomer**	*Gathering and handling of granular materials in microgravity*

coffee break

16:00 – 16:45	**Frank Spahn**	*Vertical stratification of moonlet-propellers in Saturns rings*
16:45 – 17:05	**Davide Santachiara**	*Vibration induced phenomena in granular materials instrument for parabolic flights VIP-Gran-PF*
17:05 – 17:25	**Olympia Kyriopoulos**	*A competitive way to access microgravity: suborbital space*

short break

17:45 – 18:30	**Aibing Yu**	*Discrete particle simulation of particle/particle-fluid flow at different gravity levels*

19:00-22:00 Conference dinner & at Osteria la vita e bella

Keynote **Meiying Hou** **09:00 – 09:45**

Experimental Study of Granular Dynamics in Microgravity

Meiying Hou*

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Studies on microgravity sciences in China were started in the late 1980s, mainly on material science and space biology. As an important part of microgravity sciences, Chinas first space experiment of fluid physics was completed on board the SJ-5 scientific satellite in 1997, 10 years after the initiation of the materials science space program. In 2004 the experiment of drop Marangoni migration was done on board the space ship Shen Zhou (SZ-4). In 2005 the unrecoverable capsule of SJ-8 scientific experimental satellite was used as a payload entitled to perform 9 microgravity experiments, of which 6 experiments were related to microgravity fluid science. Microgravity granular dynamics study was among these 6 experiments. In the study oscillation-driven granular motions in dense (when mean free path is much less than the characteristic scale of the system) and Knudsen regimes (when mean free path is larger than the characteristic scale of the system) are recorded and studied for the first time under microgravity in satellite SJ-8.

Microgravity environment provides an essential condition for direct study of the underlining mechanism of granular behaviors such as non-Gaussian velocity distribution, cluster formation, and compartmentalization. Dynamics of quasi-2D vibrofluidized granular gas was studied in the limit of Knudsen regime (SJ-8, 2005) [1] and in intermediate number density (ESA campaign, 2006)[2] in microgravity. Non-Gaussian velocity distri- butions are found from extreme exponential to double-peak profile, see Fig. 1(a)-(d). Generalized granular hydrodynamics is used for a phenomenological model to describe this extended boundary effect and provides an understanding of the bulk boundary effect [3] [4].

In the satellite expected to be launched in the end of 2015 clustering conditions in single and connected double cells will be studied and tested (Fig. 2). A stripe of a denser and colder gas located at the wall opposite to the driving wall is expected [5]. At sufficiently high energy loss, and within a certain spinodal interval of grain area fractions, the stripe state becomes unstable with respect to small

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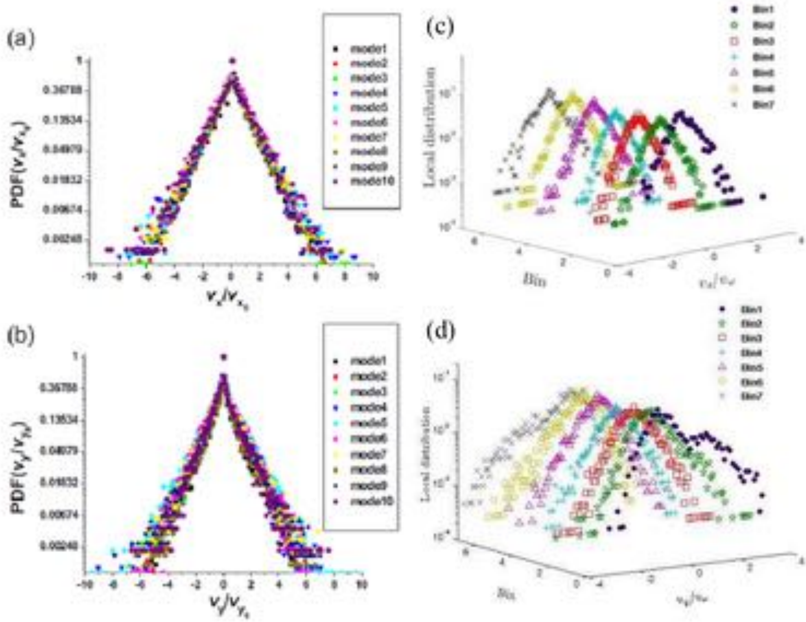

SJ-8: probability density functions of velocities in x (a) and y (b) directions in rescaled units. ESA flight campaign 2006: local distribution functions of velocities in x (c) and y (d) directions on log-linear scales. The cell is cut into 7 bins along the vibration direction to get the local distribution functions.

density perturbations in the lateral direction, unless the lateral container size is too small. Within a broader binodal, or coexistence interval, the stripe state is metastable. In both cases one observes a granular drop coexisting with vapor, or a granular bubble coexisting with liquid, along the wall opposite to the driving wall. In this experiment we modify the volume fraction of the granular system by tuning the dimensions of the boundary-shaken cell to quantitatively test the previous three-dimensional theoretical prediction based on phase separation modeling [6].

This clustering feature is also tested in a window-connected double cell for possible application of granular transportation in microgravity environment [7]. By using the so called Maxwells demon effect in granular medium, we are to answer the question on how to transport grains in zero gravity.

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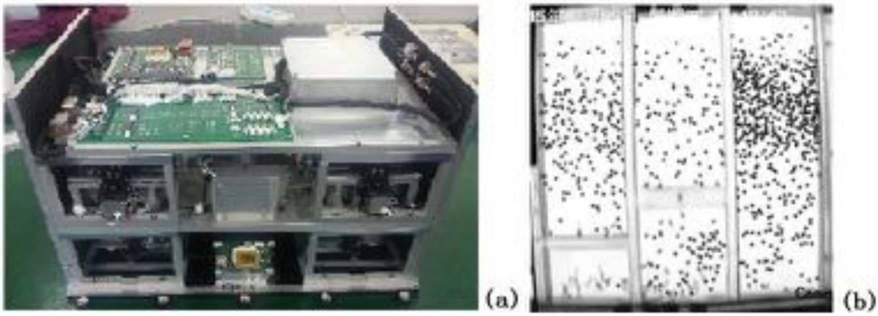

(a) Setup in the SJ-10 satellite experiment, (b) Snapshot of the distribution pattern of the drop tower experiment.

the National Natural Science Foundation of China (Grant No. 11034010), the National Natural Science Foundation of China (Grant No. 11274354, 11474326), and the Special Fund for Earthquake Research of China (Grant No. 201208011).

[1] M. Hou, R. Liu, G. Zhai, Z. Sun, K. Lu, Y. Garrabos and P. Evesque, Microgravity Sci. Technol. **20**, 73 (2008).
[2] Y. Chen, P. Evesque, M. Hou, C. Lecoutre, F. Palencia and Y. Garrabos, Journal of Physics: Conference Series **327**, 012033 (2011).
[3] Y. Chen, M. Hou, P. Evesque, Y. Jiang and M. Liu, Powders and Grains, 791 (2013).
[4] Y. Chen, M. Hou, Y. Jiang and M. Liu, Phys. Rev. E **88**, 052204 (2013).
[5] B. Meerson, T. Pöschel, P. V. Sasorov, and T. Schwager, Phys. Rev. E **69**, 021302 (2004).
[6] R. Liu, Y. Li, M. Hou and B. Meerson, Phys. Rev. E **75**, 061304 (2007).
[7] M. Hou, Y. Li, R. Liu, Y. Zhang and K. Lu, Physica Status Solidi(a) **207**, 2739 (2010).

Caroline deBeule **09:45 – 10:05**

Blowfish: An Insolation Activated Dust Layer

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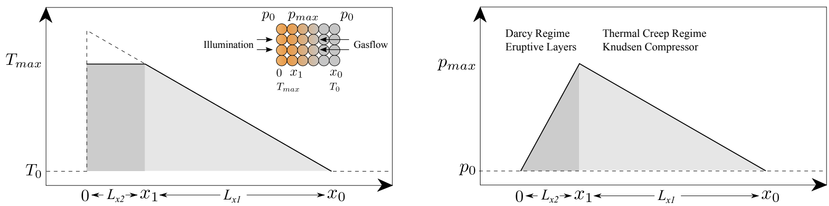
Recent experiments showed that the insolation of a dust bed in a low pressure environment leads to a gas flow through the pores of the dust bed and to a pressure increase some particle layers below the surface [1].

This is based on a developing temperature gradient within the dust bed (Fig.14), resulting in a thermal creep flow from the cold layers deep within the dust bed up to the temperature maximum [3, 4]. Additional simulations of temperature profiles in an insolated dust bed show that about the first $\sim 100\ \mu$m are on constant temperature, where no thermal creep is active [4]. Here, the gas is pumped to the surface to a pressure gradient (Darcys law).



Principle for pressure distribution for given temperature profile and open geometry (ambient pressure the same on both sides of the dust sample). L_{x2} marks the depth of the dust bed from 0 to x_1 with constant temperature and L_{x2} the part of the dust bed with a temperature gradient from x_1 to x_0 [2].

However, when the incoming radiation leads to an overpressure within the dust bed slightly too low to lift particles against cohesion and gravity, the upper layer is under high tension. This layer is called the *active layer* of a dust bed. After removing the cohesion of the dust bed by e.g. an impact, the active layer will be lifted. This is called the *Blowfish* effect.

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In experiments with basaltic dust (50 μm average grain size), an insolation of 4 kW/m^2 and average pressure of 10 mbar we find active depths of 100 to 200 μm. Additional calculations showed that the pressure driven force is higher than gravity by a factor of 2 [2].

The application of this effect can be found on Mars, where the insolation is about 700 W/m^2 at maximum and the gravity is about 1/3 of Earth's gravity. The gravity dependence was shown in parabolic flight experiments [3]. The insolation might not be high enough to lead to constant erosion of Mars, but the upper 100 to 200 μm of the insolated soil during a martian day are activated. This active layer is under constant tension and could be lifted easily due to any disturbance leading to cohesion loss.

ACKNOWLEDGMENTS

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[1] de Beule, C., Wurm, G., Kelling, T., Kuepper, M., Jankowski, T., Teiser, J. 2014, Nature Physics, 10, 17-20
[3] Knudsen, M. 1909, Annalen der Physik, 336, 205
[4] Muntz, E. P., Sone, Y., Aoki, K., Vargo, S., & Young, M. 2002, Journal of Vacuum Science Technology, 20, 214
[4] Kocifaj, M., Klačka, J., Kelling, T., & Wurm, G. 2011, Icar., 212, 935
[2] de Beule, C., Wurm, G., Kelling, T., Koester, M., Kocifaj, M. 2015, submitted to Icarus
[3] de Beule, C., Kelling, T., Wurm, G., Teiser, J., & Jankowski, T. 2013, ApJ, 763, 11

Ralph Lorenz **10:05 – 10:25**

Bedforms in a Thick Atmosphere, Low Gravity Environment - Titan

Ralph Lorenz*

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In the pressure/gravity parameter space of granular transport by fluid flow, the Titan environment occupies an interesting spot near the easy-transport frontier. While having a gravity of 1.35 ms^{-2} like our own moon, Titan has a sea-level atmospheric density four times larger than Earth. While the weak solar heating at 9AU drives modest winds, the potential for dust and sand transport was long recognized [1] [2].

It was, nonetheless, something of a surprise to find so much ($\sim 15\%$) of Titan's surface covered with giant linear dunes [3]. These megadunes (Fig. 63) are as high as 150m, tens to hundreds of km long, and typically 2-3 km apart ; in fact the same morphology and size as the largest linear dunes on Earth, in the Namib and Arabian deserts. The physical parameter controlling size appears to be the atmospheric boundary layer thickness, which despite the differences in many parameters between Earth and Titan, turns out to be about the same [1].

Dunes near Titan's equator.

The material forming the megadunes (and large areas of sand as sheets, or unresolved small dunes, may also exist) is not known in detail, but broadly appears to be organic, derived ultimately from atmospheric photochemistry. It may have been processed by washing, flocculation, cementation or other liquid-mediated processes in Titan's methane-based hydrological cycle, and/or by sintering. The

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material is known to be dark, to have a low dielectric constant, and to be correlated with a spectral signature of aromatic compounds - it is probably an assemblage of polyaromatic cyclic hydrocarbons (PAHs) and their nitrogen-substituted variants. Although the photochemical feedstock ('tholin') precipitates as submicron haze particles, the pathway to grains with a threshold windspeed of $\sim 1\mathrm{ms}^{-1}$, as indicated by global circulation models, is not known. Such grains imply a size of $\sim$200-400 μm [1], [5]. It seems likely that electrostatic effects could be significant for the transport of such sand on Titan.

The characteristic grain motion scales (saltation length, drag length, saturation length etc.) of such grains is rather short (few to tens of cm) such that much higher resolution than is presently available from Cassini ($\sim$ 300m) is needed to study aeolian bedforms on Titan. Titan's low-gravity, thick-atmosphere environment permits many possible vehicles (hot air balloons, aeroplanes, etc.) to conduct such observations in future.

ACKNOWLEDGMENTS

This work was supported by the Cassini project via NASA Grant NNX13AH14G.

[1] R. Lorenz et al., J. Geophys. Res, **88**, 26,377 (1995).
[2] R. D. Lorenz and J. Zimbelman *Dune Worlds: How Wind-Blown Sand Shapes Planetary Landscapes* (Springer, New York, 2014).
[3] R. Lorenz et al., Science, **312**, 724 (2006).
[4] R. Lorenz, Icarus, **205**, 719 (2010).
[5] R. Lorenz, Icarus, **230**, 162 (2014).

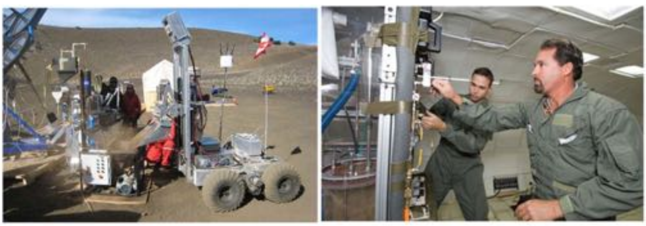
Keynote | **Philip Metzger** | **11:00 – 11:45**

Low Gravity Granular Physics: a Key to the Future of Humanity

Philip Metzger*

Florida Space Institute, University of Central Florida, Orlando, Florida, USA

From its origins in the Agricultural Revolution until today, human civilization has experienced dramatic growth. The potential for ever greater things is bright if we escape the resource limitations of our planet. The economic barrier to establishing a solar system civilization is very high, but a feasible scenario is developing to get over it. Water that has been mined from the Moon and Near Earth Asteroids can be sold profitably as rocket propellant to boost communications satellites from low Earth orbit to geosynchronous orbit, dramatically cutting the launch costs. The information-driven demand for these satellites is growing, so space mining and industry is starting to make economic sense. However, this scenario assumes there will be governmental assistance financing the in-space infrastructure - a propellant transfer depot to collect the mined water and refuel the space tugs. Government space agencies have an incentive to establish this infrastructure, because space-mined water is seven times less expensive than water launched from Earth, cutting the overall cost of human-crewed Mars missions by a factor of three to five. Nevertheless, space agencies cannot build their mission architectures around this idea until the technologies are provably mature. Thus, low gravity granular physics seems to be in the center of the path to humanity's future. We need advances to land, drive, mine, convey, chemically process, and build structures on or with regolith on the Moon, asteroids and Mars. This talk will give an overview of this developing economic scenario and some of the key technology work that has been accomplished so far, highlighting the need for future advances.



Left: "Dust to Thrust"field test in Hawaii, with excavator delivering volcanic ash into regolith conveyance system for chemical processing to extract oxygen. Right: Reduced gravity flight test of regolith conveyance system.

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Paul Sanchez **11:45 – 12:05**

Rotational Disruption of Self-Gravitating Granular Aggregates

Paul Sánchez[1,*] and Daniel J. Scheeres[2]

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During the last 15 years or so, the Planetary Sciences community has been using DEM simulation codes to study small NEOs. In general these codes treat gravitational aggregates as conglomerates of spherical particles; a good approximation given that many asteroids are self-gravitating granular media. Unfortunately, the degree of sophistication of these codes, and our own understanding, has not been high enough as to appropriately represent realistic physical properties of granular matter. In particular, angles of friction (θ) and cohesive strength (σ_c) of the aggregates were rarely taken in consideration and this could have led to unrealistic dynamics, and therefore, unrealistic conclusions about the dynamical evolution of small NEOs.

In our research, we explore the failure mechanics of spherical (r=71 m) and ellipsoidal (r_1=92 m) self-gravitating aggregates with different angles of friction and values for their cohesive strength, in order to better understand the geophysics of rubble-pile asteroids. In particular we focus on the deformation and different disruption modes provoked by an always increasing angular velocity (spin rate).

We use a computational code that implements a Soft-Sphere Discrete Element Method. The code calculates normal, as well as, frictional (tangential) contact forces by means of soft potentials and the aggregate as a whole mimics the effect of non-spherical particles through the implementation of rolling friction. Cohesive forces, and a cohesive stress, are calculated as the net effect of the sum of the van der Waals forces between the smaller regolith, sand and dust (powder) that are present in real asteroids [1]. These finer materials form a matrix of sorts that holds the bigger boulders together.

For this, we use self-gravitating aggregates formed by thousands of spheres and a soft-sphere DEM code to explore the effect of the variation of two parameters, angle of friction and cohesive strength, on their disruption process. We have chosen to use spherical and ellipsoidal shapes as the starting point of the evolution as these are classical forms that could also be studied analytically. The aggregates were slowly spun up to disruption controlling for angle of friction, cohesion

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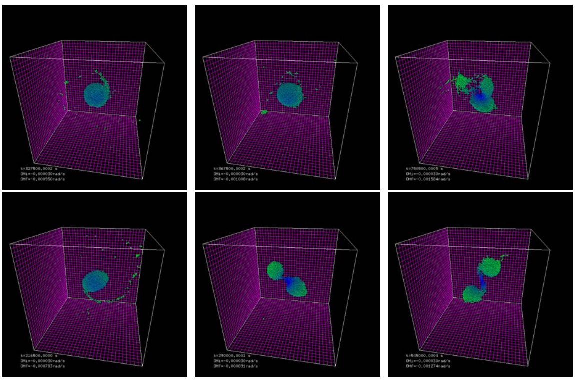
and global shape. How much each aggregate deformed before disruption was directly related to the angle of friction. The greater it was, the less the aggregate deformed before disruption. Cohesive forces on the other hand controlled the mode of disruption and maximum spin rate and showed that the aggregates could disrupt by shedding particles or groups of particles from the equatorial region. For high values of cohesive strength, the pieces that detached from the initial aggregate were sizable enough as for the disruption process to be seen as a fission. This revealed that the change from shedding to fission is continuous and therefore, they should not be seen as different disruption processes but just as two ends of the spectrum.

The figure shows the deformation and disruption of three initially spherical aggregates (left) and three initially ellipsoidal aggregates (right) with increasing cohesive strength from left to right ($\theta \approx 35°$). Through scaling arguments we could also see these aggregates as having the exact same $\sigma_c = 25$ Pa but different sizes.

A closer look at the spherical aggregates (35°) showed that the reshaping of the bodies was not symmetrical. A granular aggregate cannot be completely homogeneous unless its particles are arranged in a crystalline structure and we purposely avoided this scenario. This means that the reshaped body would acquire an asymmetrical shape, similar to that of 1999 KW4 and sometimes would even form a binary system. For ellipsoidal aggregates, this meant the formation of tear-drop shapes and pairs. The failing of the granular structure is ultimately controlled by the inter-particle forces which in turn form force chains. What this could mean for the internal structure of a rubble-pile asteroid will be explored during the conference [2].



Deformation and disruption of three initially spherical (top left) and three ellipsoidal (bottom right). From left to right the aggregates have greater cohesive strength (or same strength and diminishing size)

[1] P. Sánchez and D. J. Scheeres, Meteoritics & Planetary Science **49**, 788 (2014).
[2] P. Sánchez and D. J. Scheeres (ACM, Finland, 2014).

Ingo von Borstel **12:05 – 12:25**

The Brazil Nut effect under varying gravitation and excitation

Ingo von Borstel,[1,*] Jürgen Blum,[1] Carsten Güttler,[2] and Rainer Schräpler[1]

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We present laboratory experiments of a vertically vibrated granular medium consisting of 1mm diameter glass beads with embedded 8mm diameter intruder glass beads. The experiments by [1] show a dependency of the Brazil Nut effect with the ambient gravity but do not allow to constrain well the functional dependence. These new experiments are performed in the laboratory using a linear motor, allowing covering a broader effective gravity range for the experiments, ranging from 0.25g to 2.0g . These measurements also allow a detailed assessment of the influence of different excitation accelerations. We use the data of the derived rise velocities to compare with and to look into the validity of models (e.g. Knight et al, Grossman or Rajchenbach [2–4])

ACKNOWLEDGMENTS

The parabolic flight was kindly provided by ESA, the hardware, R.S and I.v.B are funded by the DLR through grant 50WM1236. We thank M. Rott for the flight opportunity and P. Reiss, P. Hager and R. Purschke for help with the parbolic flight experiments

[1] C. Güttler, I. von Borstel, R. Schräpler and J. Blum, Phys. Rev E **87** (2013)
[2] J. B. Knight, E. E. Ehrichs, V. Y. Kuperman, J. K. Flint, H. M. Jaeger and S. R. Nagel, Phys. Rev. E **54**, 5726 (1996)
[3] E. L. Grossman, Phys. Rev. E **56**, 3290 (1997)
[4] J. Rajchenbach, EPL **16**, 149 (1991)

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Keynote **Mihaly Horanyi** **14:00 – 14:45**

Characterizing the Lunar Regolith by Laboratory and Space Experiments

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This talk will review the recent observations by the Lunar Dust Experiment (LDEX)[1] onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE)[2] mission, and their relevance to improve our understanding and characterizing the lunar regolith. Additionally, recent laboratory experiments will also be described that address the possible effects of electrostatic charging on the mobilization and transport of small dust particles on the surfaces on airless planetary bodies.

LDEX discovered a permanently present dust cloud engulfing the Moon. The size, velocity, and density distributions of the dust particles are consistent with ejecta clouds generated from the continual bombardment of the lunar surface by sporadic interplanetary dust particles. Intermittent density enhancements were observed during several of the annual meteoroid streams, especially during the Geminids. In addition to the mass and speed of the impacting particles, in a significant fraction of the events, LDEX also recorded the electrostatic charge of the dust grains before their impact of our instrument.

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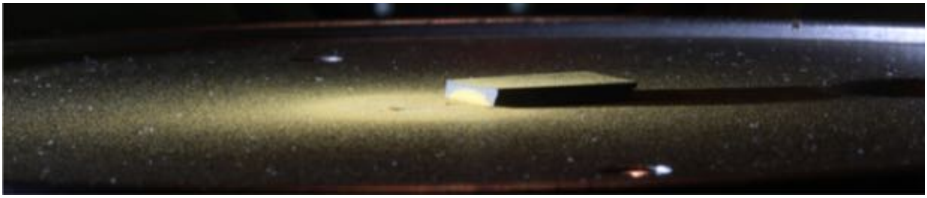

JSC-Mars-1 (< 50um diameter particles) dust pile (3 mm in diameter, 1 mm high) initially rests on a graphite surface (22 cm in diameter, electrically floated). An insulating block (2 mm high) is placed 3 mm away from the dust pile. Energetic electrons (130 eV beam) come from the top to the dust surface and create a dense plasma (n > 109cm^3). The picture is taken after running for 5 minutes. Dust particles landed on the higher block and spread out on almost the entire graphite surface. *Acknowledgement:* The photo was taken by X. Wang, University of Colorado on 2/12/2015.

We have conducted a series of laboratory experiments to investigate to effects of charging of dusty regolith surfaces exposed to UV and plasma, and the subsequent possible mobilization and transport of small grains[3]. FIG. 1 shows an example of a spreading dust pile that was confined before its exposure to a plasma flow. On the time-scale of minutes the pile spreads into a nearly uniform layer of dust, possibly explaining some of the similar surface features observed on asteroids, and more recently comet 67P/Churyumov-Gerasimenko, the target of the Rosetta mission[4].

Experimental studies of the interaction of the lunar regolith with the environment have been almost exclusively based on simulants (JSC-1, MLS-1), which only reproduce some aspects of the genuine regolith. The chemical and mineralogical properties (including moisture and ice content), the surface roughness, the effective surface contact area, or the effective packing fraction, for example, all might have large effects on the effects of dust impactcs, plasma and UV exposure, or in situ resource utilization (ISRU) activities. The number of parameters that define all of the critical physical and geotechnical properties of the regolith can be very large, which creates a complicated and potentially intractable problem to isolate and assess the effects of any individual characteristic through experiments. We will also describe a family of simplified but well characterized regolith reference surfaces to be used in dust impact and charging experiments, as well as for the characterization of the geotechnical properties of surfaces for their ISRU potential.

ACKNOWLEDGMENTS

This work was supported by NASA. The analysis and interpretation of the LADEE/LDEX results were done in collaboration with J. Szalay. Jürgen Schmidt, and S. Kempf. The laboratory experiments discussed in this talk were led by X.

Wang

[1] M. Horányi, Z. Sternovsky, M. Lankton, C. Dumont, S. Gagnard, D. Gathright, E. Grün, D. Hansen, D. James, S. Kempf, B. Lamprecht, J. Szalay, R. Srama, and G. Wright, Space Science Reviews, **185**, 93 (2014).
[2] R. C. Elphic, G. T. Delory, B. P. Hine, P. Mahaffy, M. Horanyi, A. Colaprete, M. Benna, and S. Noble, Space Science Reviews **185**, 3 (2014).
[3] X. Wang, M. Horanyi, and S. Robertson, IEEE Transactions on Plasma Science **39**, 2730 (2011).
[4] N. Thomas, *et. al.*, Science **347** (2015).

Achim Sack **14:45 – 15:05**

Granular Dampers in Microgravity

Achim Sack,* Jonathan Kollmer, Michael Heckel, and Thorsten Pöschel

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By means of experiments under microgravity conditions, we investigate the dissipative behaviour of sinusoidally driven boxes which are partly filled with granular material. The boxes are mounted on a linear bearing which is sinusoidally driven by a motor. We record the force acting on the boxes and the instantaneous velocity. To calculate the dissipated energy, we integrate the product of the force and velocity over one period of the imposed oscillation.

Depending on the amplitude of driving, A, we observe two distinct modes of granular dynamics (and thus different damping behaviour) separated by a well defined threshold A_0 (see Fig. 63): For large amplitudes, $A > A_0$, the granulate is found in the collect-and-collide regime where the center of mass of the granulate moves synchronously with the driven container (see Fig. 63, right inset). This corresponds to the motion of a quasiparticle interacting perfectly inelastic with the container walls. For weak forcing, $A < A_0$, the interaction between granulate and box leads to desynchronisation and the granular material exhibits a gaslike behavior (see Fig. 63, left inset). Interestingly, at the edge of stability of the collect-and-collide regime, $A = A_0$, we obtain maximal efficiency in damping.

For both regimes, the experimental results may be collapsed to a single "master curve" independant of filling fraction, mass of granulate, particle properties, particle number, and frequency of the vibration. Based on the one-particle model and on the theory for granular gases we derive a model without any fitting parameters that describes the experiment up to good agreement.

ACKNOWLEDGMENTS

We thank the German Science Foundation (DFG) for funding through the Cluster of Excellence Engineering of Advanced Materialsâ as well as the European Space Agency (ESA) for funding the parabolic flight campaign.

[1] A. Sack, M. Heckel, J. E. Kollmer, F. Zimber and T. Pöschel Phys. Rev. Lett. **111**, 018001 (2013).

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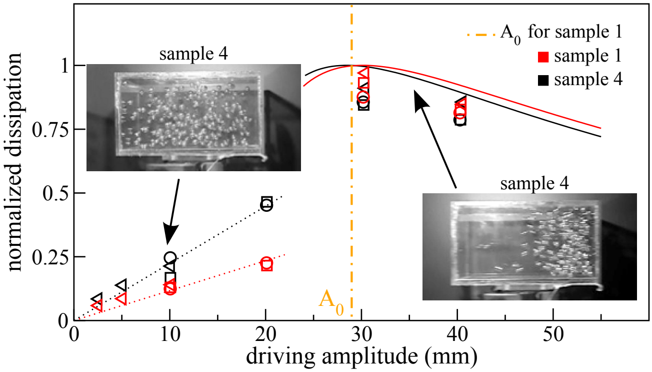


Normalized dissipated energy per period of external vibration. Symbols: Experimental data. Solid lines: Solution of the impact model, valid for $A > A_0$. Dotted lines: Dissipation rate for the gaseous regime, $A < A_0$. Insets: Snapshots from high-speed recording illustrating the two distinct regimes: Gas-like regime (left) and collect-and-collide (right)

[2] J. E. Kollmer, A. Sack, M. Heckel and T. Pöschel New J. Phys. **15**, 093023 (2013).
[3] A. Sack, M. Heckel, J. E. Kollmer and T. Pöschel Granul. Matter **17**, 73-82 (2015).
[4] J. E. Kollmer, M. Tupy, M. Heckel, A. Sack and T. Pöschel Phys. Rev. Applied **3**, 024007 (2015).

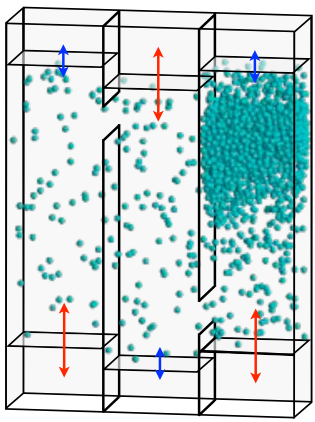
Eric Opsomer **15:05 – 15:25**

Gathering and Handling of Granular Materials in Microgravity

E. Opsomer,* F. Ludewig, and N. Vandewalle

University of Liege

Driven granular gases present rich dynamical behaviors. Given the dissipative character of the collisions between the constitutive particles of the medium, dense and slow regions may appear in the system. These clusters emerge naturally during cooling phenomena but another, dynamical, clustering can be observed for continuously excited systems [1]. In our work, the physical processes that trigger the transition from a granular gas to a dynamical cluster are evidenced through molecular dynamics simulations, realized in the frame of the ESA SpaceGrains project. Physical arguments, based on relaxation times and energy propagation, deliver an analytical prediction for the gas cluster transition of a granular media [2]. This new control of the granular clustering provides an interesting way to gather particles in microgravity and, furthermore, to achieve granular transport since the position as well as the dynamics of the cluster can be controlled by a precise tuning of the driving parameters [3].



Dynamical clustering in a driven granular gas under microgravity conditions. Grain colors depend on a local density criterion.

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This work has been supported by Prodex (Belspo, Brussels) and the European Space Agency program TT VIP- GRAN/SpaceGrains. We also thank the Shape-SPS project (Wallonia) for supporting the development of our numerical model.

[1] E. Opsomer, F. Ludewig and N. Vandewalle, Phys. Rev. E. **84**, 051306 (2011).
[2] E. Opsomer, F. Ludewig and N. Vandewalle, Europhys. Lett. **99** 40001 (2012).
[3] M. Noirhomme, E. Opsomer, N. Vandewalle and F. Ludewig, Eur. Phys. J. E., accepted (2015).

Keynote **Frank Spahn** **16:00 – 16:45**

Vertical stratification of moonlet-propellers in Saturn's rings

F. Spahn,* M. Seiß, and H. Hoffmann

University of Potsdam, Institute of Physics and Astronomy Karl-Liebknecht-Str. 24/25, 14476 Potsdam

Small moons (size: hundred meters up to sub-kilometer) embedded in the dense and bright rings of Saturn are too small to get detected by the cameras of the *Cassini*-spacecraft. However, the gravity of these Moonlets carve Propeller-structures [3] in the adjacent ring matter so that these bod- ies become visible for the *Cassini*-detectors. The theoretical prediction of Propellers gave rise to the detection of meanwhile more than 150 ring moons [2, 4, 5].

Because of the extreme flatness of the dense Saturn's rings of only a few meters the Propeller-structures have been believed to be practically two-dimensional. Surprisingly, in August 2009 the equinox constellation at Saturn's rings (sunset at the rings) revealed the Propellers to cast promi- nent shadows onto the flat rings pointing to a considerable vertical extent of these Moonlet-induced features. Here we report on an extension [1] of the gravitational scattering model to 3D which describes quantitatively the shadow pattern, yielding estimates for the hight of the Propeller of about the radius of the Moonlet, and further, allowing to measure remotely the collision frequency in the Propeller-region (5 - 10 collisions per orbit).

[1] H. Hoffmann, M. Seiß, and F. Spahn, *Astrophys. J.*, **765**, L4 (2013).
[2] F. Spahn and J. Schmidt. *Nature* **440**, 614 (2006)
[3] F. Spahn and M. Sremčević, M. *Astron. and Astrophys.* **358** 368 (2000).
[4] M. Sremčević, J. Schmidt, H. Salo, M. Seiß, F. Spahn, and N. Albers, *Nature* **449** 1019 (2007).
[5] Tiscareno, M. S., Burns, J. A., Hedman, M. M., Porco, C. C., Weiss, J. W., Murray, C. D., and Dones, L. *Nature*, **440** 648 (2006).

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Davide Santachiara **16:45 – 17:05**

Vibration Induced Phenomena in Granular Materials Instrument for Parabolic Flights VIP-Gran-PF

Davide Santachiara,[1,*] Luca Recanatesi,[1] Andrea Pellegrini,[1] Marco Martella,[2] and Olivier Minster[2]

[1]*DTM srl, Modena - Italy*
[2]*ESA-ESTEC*

VIP-Gran-PF is an instrument compatible with the environment of the Airbus 0-g flying parabolic trajectories, namely low gravity for up to 20 seconds.
VIP-Gran-PF will support experiments on the dynamics and statistical behaviour of an ensemble of solid beads confined in a test chamber, while subject to variable mechanical vibrations. These research activities are coordinated in the framework of the International Topical Team on granular materials (spacegrains.org).
This instrument, which is being developed by DTM under ESA contract 4000111622/14/NL/FC, has already completed its design activities and has started the manufacturing and integration phases.

Two pistons moved by linear voice-coil motors, will be in charge of transferring the selected vibration stimuli to the beads inside the test chamber: through the variation of piston oscillation amplitude (from 0.2 mm to 25 mm peak-to-peak) and frequency (from 1 to 50 Hz), it will be possible to set the acceleration level imparted to the beads up to 5 g.

The instrument allows to mount different type of experiment cells. DTM is currently developing the following three first test cells for investigations on granular media:

- 3D Cell: it has a test chamber of 60 mm (W) x 30 mm (H) x 30 mm (D) where beads will move within an air media. This cell will be also provided with a bead injection device (called "bead feeder") to allow to increase the number of beads in the test volume.
- Quasi-2D Cell: this cell has all the characteristics of the 3D cell (air media and bead feeder device), with the only exception of having the test volume height reduced to only 5 mm, to allow a simpler particle tracking.
- Wet Cell: this cell has the same overall dimensions of the 3D Cell and its unique feature is that it is designed to be watertight to contain beads in an

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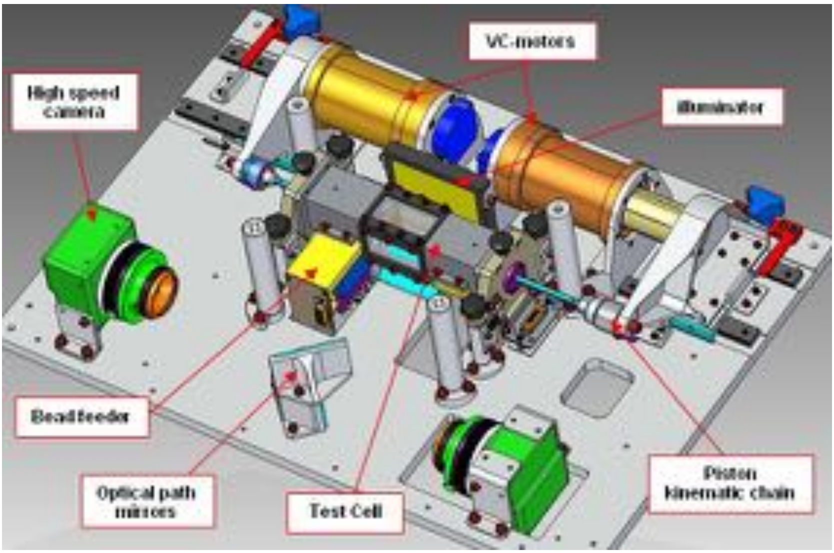
index-matching liquid media. This cell will allow to study stress-induced birefringent effects during beads compaction and sound propagation in a granular media.

For what concerns the dimensions of the beads representing the granular media, the 3D and Quasi-2D Cell will allow to use beads having a diameter ranging from 1 mm to 2 mm, while inside the Wet Cell it will be possible to inject beads with a diameter ranging from 0.5 mm to 1 mm.

In order to provide useful data about sound propagation and collisions between pistons and beads, an impact sensor is mounted on top of each cells piston (except in the Quasi-2D Cell) while two accelerometers will monitor the acceleration level of the applied stimuli.

The VIP-Gran-PF instrument will also allow the observation of the ongoing experiment by means of two high-speed cameras capable of reaching a frame rate of 1000 fps with a resolution of 1024x1024 pixels. The onboard workstation and electronics will allow, for each parabola, high-frequency acquisition of both video-images and sensor signals as well as programming the required experiment profiles (piston frequency, amplitude, type of oscillation).



VIP-Gran-PF core experiment layout

Olympia Kyriopoulos 17:05 – 17:25

A COMPETITIVE WAY TO ACCESS MICROGRAVITY: SUBORBITAL SPACE

Olympia Kyriopoulos*

Telespazio VEGA Deutschland GmbH, Darmstadt, Deutschland

We are about to experience a major shift in suborbital space access driven by new entrepreneurial ventures that are developing suborbital commercial systems to serve both existing and new markets. These new ventures are focusing their efforts on suborbital reusable launch vehicles (sRLV) capable of crossing the threshold of space (100km) and offering around one to four minutes of microgravity. A broad range of sRLV ventures are underway: some are still in the design phase, others are in their final testing phase, while a few are already operational. Their first revenue earning flights will carry science and engineering payloads and some will later fly space tourists. An overview of the current suborbital and microgravity capabilities will be given and then compared to the sRLV systems, which vary between vertical takeoff/landing rockets and horizontally launched winged vehicles. Though more technically challenging than expendables, reusable vehicles amortize their production costs over a larger number of flights and thereby reduce their per flight unit cost. They will also fly more frequently and achieve much higher levels of reliability and safety than expendable vehicles and so offer a more flexible, efficient, inexpensive, frequent access to space for payloads and spaceflight participants. A new spaceflight industry is growing to exploit high flight rates and relatively low cost markets. Research areas such as biology, physics, advanced materials and Earth science can benefit from suborbital space access, while commercial companies can boost their research and development sectors (e.g. pharmaceutical business). Telespazio VEGA has been actively promoting this rapidly emerging market of commercial suborbital spaceflight and has taken initial steps to connect this growing market with first flight opportunities. As most of these ventures are based in the U.S., these steps are also enabling Non-U.S. researchers to take maximum advantage of this new, competitive way to exploit microgravity.

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Suborbital Space Flight.
Telespazio VEGA Deutschland: Access to microgravity conditions in space. Over the last decade, Telespazio VEGA Deutschland has been actively promoting the rapidly emerging market of commercial suborbital space flight. It has pioneered initial steps to interconnect this growing market with first flight opportunities that are more flexible, efficient and cost-effective. Researchers should take maximum advantage of this new, competitive way to exploit microgravity.
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Keynote **Aibing Yu** **17:45 – 18:30**

Discrete Particle Simulation of Particle/Particle-Fluid Flow at Different Gravity Levels

Shibo Kuang,[1] Kejun Dong,[2] and Aibing Yu[1,*]

[1] *Department of Chemical Engineering, Monash University, Clayton*

[2] *Institute for Infrastructure Engineering, University of Western Sydney, Australia*

Particulate materials are widely encountered in outer space where the gravity level varies, showing complicated behaviors that are not fully understood. This talk will discuss the micromechanic modelling and analysis of the particle/particle-fluid flows at different gravity levels. The numerical models used were based on DEM (discrete element method) approach. The applicability of the models has been demonstrated by two case studies: the particle dispersion in a horizontally vibrating vessel with round corners under zero gravity and the jet-induced cratering process in a granular bed at different gravity levels.

For the first case, the DEM approach was used and validated by the good agreement between the simulated and measured number concentration distributions results. The effects of key variables, including overall particle number concentration and vibration amplitude and frequency, were studied by a series of controlled numerical experiments. The particle flow in the vessel was analyzed by the detailed particle scale information obtained from the simulations. The results were used to reveal the mechanisms and clarify some speculations of the particle flow observed in the experiments. In particular, it was found that the conveying velocity generated by the round corner can be correlated to the velocity amplitude, and so is the overall kinetic energy of the particles inside the vessel.

For the second case, the combined approach of CFD (Computational Fluid Dynamics) for gas phase and DEM for solid phase was adopted and verified by the good agreement of calculated and measured crater depth and crater shape in the cratering regime of Diffusion Driven Flow. The sensitivity of numerical results to model parameters such as restitution coefficient, sliding friction coefficient and Young's modulus was also examined. Then, the effects of jet velocity and gravity level were quantified, followed by a detailed analysis of flow characteristics and forces between particles, as well as between particles and fluid, to understand the underlying mechanisms. The results showed that the cratering under the condition considered is mainly caused by the radial motion of particles, followed by the upward motion along the crater sides. This behaviour is attributed to

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large horizontal components of fluid drag force and pressure gradient force on the lower part of crater while the large vertical components on the upper part. Based on the simulated results, two equations were respectively formulated to estimate the asymptotic crater depth and crater width at different gravity levels.

All the results suggest that the DEM-based approaches could provide a convenient way to study particulate systems at different gravity levels.

Friday

09:00 – 09:45	**Tilman Spohn**	*Rosetta/Philae at comet 67p Churyumov-Gerasimenko*
09:45 – 10:05	**Nicole Albers**	*Saturn's rings - Theory and observations by Cassini UVIS and ISS*
10:05 – 10:25	**Stephen Schwartz**	*Low-speed Granular Dynamics - Hypervelocity impacts in low gravity*

coffee break

11:00 – 11:45	**Ernesto Altshuler**	*Settling into dry granular media in different gravities*
11:45 – 12:05	**Christine Hartzell**	*Towards a model of tribocharging for planetary science applications*
12:05 – 12:25	**Gonzalo Tancredi**	*Granular media in the context of Small Solar System Bodies*

lunch break

14:00 – 14:45	**Wolfgang Losert**	*Convection in 3D granular flows*
14:45 – 15:05	**Jens Biele**	*Drivers, requirements and recent projects on interaction of small body regolith with landers, probes and sampling devices - Philae, MASCOT and beyond*
15:05 – 15:25	**Christina Knapek**	*Complex plasma research in microgravity*

coffee break

16:00 – 16:45	**Gerhard Wurm**	*The granular nature of (pre)-planetary environments studied under different gravity conditions*
16:45 – 17:05	**Devaraj van der Meer**	*On creating macroscopically identical granular systems with different numbers of particles*

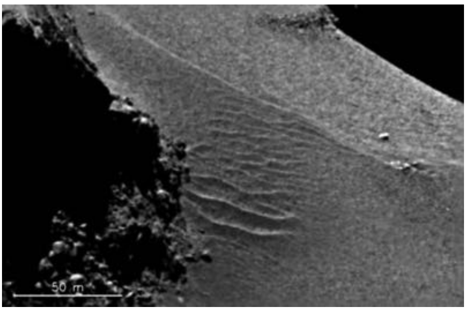
Keynote	Tilman Spohn	09:00 – 09:45

Rosetta/Philae at Comet 67p Churyumov-Gerasimenko

Tilman Spohn*

DLR Institute of Planetary Research, Berlin

The Rosetta spacecraft is in orbit around the nucleus of comet 67p Churyumov-Gerasimenko since August 2014 and on November 12, 2014, Philae landed in a region of the nucleus that was named Abydos. Philae operated for almost 60h before it ran out of battery charge. The lighting conditions at Abydos are such that the secondary battery could not be charged but that will change after April. Rosetta with its camera packages OSIRIS and NAVCAM has provided a wealth of images that show a bizarre world. The comet is already active but even more interesting perhaps are morphological features that attest to past surprisingly strong activity. Among these are aeolian features like ice sand dunes, wind tails and bed forms suggesting local winds. Other witnesses of past activity are pit holes and cracks. The data of the two spacecraft are still being interpreted but among the first results are a D/H ratio incompatible with the idea that the water on Earth is from comets like 67p, a surprising strength of the near surface layers that are believed to be sintered porous ice underneath a dust mantle of varying thickness, a porosity somewhere between 60 and 80are ongoing to locate the lander after its involuntary extended flight across the surface and the community is looking forward to increased activity as the comet approaches perihelion (August 13). Hope pertains that Philae can be reactivated this spring.



Aeolian ripples in the Hapi region of the comet [1].

[1] Nicolas Thomas, *et al.,* Special Issue on Rosetta, Science, **347,** issue 6220, aaa0440 (2015).

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Nicole Albers **09:45 – 10:05**

Saturn's rings - Theory and Observations by Cassini UVIS and ISS

Nicole Albers,[1,*] Miodrag Sremčević,[1] Ana H.F. Guimarães,[2] and Larry W. Esposito[1]

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Saturn's rings are the most prominent ring system in our Solar system and one example of granular matter in space. Dominated by tides and inelastic collisions the rings extent radially more than $130,000\,\mathrm{km}$ and are at the same time less than $100\,\mathrm{m}$ thick. Their particles range in size from microns to hundreds of meters. Observations made by the Cassini spacecraft currently in orbit around Saturn reveal unprecedented detail of the large and small scale structures abundant throughout the system. These include: self-gravity wakes ($50-100\,\mathrm{m}$), "straw/ropy" structures ($1-3\,\mathrm{km}$), overstable waves ($100-300\,\mathrm{m}$), density waves (few km to few tens of km), gaps, ringlets, and propeller structures created by embedded moonlets. High-resolution measurements by the Cassini Ultraviolet Spectrometer (UVIS) High Speed Photometer (HSP) and the Imaging Science Subystem (ISS) further provide evidence for clumps in the C ring, Encke gap ringlets, and F ring as well as for the presence of sub-km structure in perturbed regions of the rings such as strong density waves and the outer edges of the A and B ring. These perturbed regions, driven by resonances with external moons, undergo periodic phases of compression and relaxation that correlate with the presence of structure, implying structure formation on time scales as short as one orbit. Kinematic studies of the B ring edge show that the expected m=2 pattern is changing in time and that deviations from it are exceptionally strong.

These detections point toward a very dynamical ring system indicating ongoing aggregation and fragmentation.

ACKNOWLEDGMENTS

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Stephen Schwartz **10:05 – 10:25**

Low-speed Granular Dynamics - Hypervelocity Impacts in Low Gravity

Stephen R. Schwartz,* Yang Yu, and Patrick Michel

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The study of motions of granular material lofted at low speeds from the surface of a small body as the result of a hypervelocity impact has been left largely unexplored to date—the speeds of such material might be comparable to the escape speed of the small body, five orders of magnitude below the impactor speed in the case of the AIDA mission. The NEOShield Project, funded by the European Commission in its FP7 program, is primarily, but not exclusively, a European consortium of research institutions that aims to analyze promising mitigation options and provide solutions to the critical scientific and technical obstacles involved in confronting threats posed by small bodies that cross EarthÕs orbit. An important component of the work package is the design a general NEO defense strategy based upon momentum transfer via kinetic impact [1]. Relatedly, AIDA is a joint NASA-ESA mission in Phase A/B1 study comprising the NASA Double Asteroid Redirection Test (DART) mission, which is to act as a test of our ability to deflect an asteroid using a kinetic impactor, and the ESA Asteroid Impact Monitor (AIM) rendezvous mission, an observer spacecraft that would characterize the target and the impact outcome. In order to address concerns over potential observational and mechanical effects of lingering dust and debris, information about the ejecta produced by such an impact is of particular importance to the mission profile of an observer satellite (e.g., AIM). Here we discuss some of the details of the numerical issues involved in assessing the ejecta fate in the framework of a hypervelocity kinetic impactor approach to NEO threat mitigation as part of a specific work package of NEOShield, and with the AIDA framework in mind.

In order to generate an ejecta field, the late-stages of the impact phase must be solved; we do so in three different ways and compare the results: by using a hydrocode to compute the impact outcome [2], solving for the initial ejecta positions and velocities using known scaling laws [3]; Fig. 63, and by using an N-Body approach to compute the impact [4] as well as the resulting ejecta

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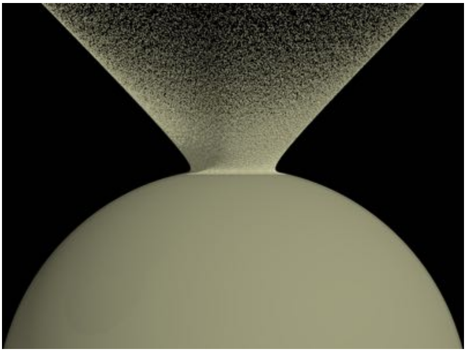
field. Each approach, having its own unique strengths and limitations, will be discussed.



An N-body simulation using ejecta particle velocities solved for with scaling laws from [3]: a bowl of 641,586 particles representing a portion of the surface of an asteroid that suffers a kinetic impactor strike is embedded into the surface of a sphere that represents the entire asteroid; the particles are then ejected.

ACKNOWLEDGMENTS

This study is performed in the context of the NEOShield Project funded under the European CommissionÕs FP7 program agreement No. 282703. Most of the computation was performed using the Beowulf computing cluster (`YORP`), run by the Center for Theory and Computation at the University of Maryland's Department of Astronomy. For data visualization, the authors made use of the freeware, multi-platform ray-tracing package, Persistence of Vision Raytracer (`POV-Ray`).

[1] A. W. Harris et al. Acta Astronautica **90**, 80 (2013).
[2] M. Jutzi and P. Michel, Icarus **229**, 247 (2014).
[3] K. Housen and K. Holsapple, Icarus **211**, 856 (2011).
[4] S. R. Schwartz et al., Planet. Space Sci. **103**, 174 (2014).

Keynote **Ernesto Altshuler** **11:00 – 11:45**

Settling Into Dry Granular Media in Different Gravities

E. Altshuler,[1,*] H. Torres,[1] A. Gonzalez-Pita,[1] G. Sanchez-Colina,[1] C. Perez-Penichet,[1] S.Waitukaitis,[2] and R. C. Hidalgo[3]

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While the penetration of objects into granular media is well-studied, there is little understanding of how objects settle in gravities, g_{eff}, different from that of Earth - a scenario potentially relevant to the geomorphology of planets and asteroids and also to their exploration using man-made devices. By conducting experiments in an accelerating frame, we explore g_{eff} ranging from 0.4 g to 1.2 g. Surprisingly, we find that the rest depth is independent of g_{eff} and also that the time required for the object to come to rest scales like $g_{\mathit{eff}}^{-1/2}$. With discrete element modeling simulations, we reproduce the experimental results and extend the range of g_{eff} to objects as small as asteroids and as large as Jupiter. Our results shed light on the initial stage of sedimentation into dry granular media across a range of celestial bodies and also have implications for the design of man-made, extraterrestrial vehicles and structures.

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Christine Hartzell 11:45 – 12:05

Towards a Model of Tribocharging for Planetary Science Applications

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In low gravity environments, such as those found on asteroids and the Moon, non-gravitational forces become significant and may dictate the behavior of dust grains. Specifically, it has been shown that cohesion may be responsible for preventing the loss of surface material on fast spinning asteroids [1]. Additionally, it has long been hypothesized that electrostatic forces, due to the interaction of charged dust grains with the solar wind plasma, may result in the lofting or levitation of dust grains above asteroids and the Moon [2]. In addition to becoming charged due to exposure to the local plasma environment, dust grains may also experience tribocharging - where charge is exchanged between grains during collisions or sliding contacts. Spacecraft-surface interactions, such as a wheel rolling through dust or drilling, may result in tribocharging. Tribocharging may also occur in the natural environment during landslides. We are interested in modeling charge exchange due to tribocharging and the grains' subsequent interaction with each other and with the near-surface plasma environment.

Tribocharging between identical insulators is not well understood. We have developed a model for the average charge on species in a bidisperse (two grain species of different sizes, but the same material) mixture of grains, based on the work by Lacks and Levandovsky [3]. Lacks and Levandovsky propose that charge separation in a bidisperse mixture occurs when electrons trapped in high energy states are transferred between grains and to lower energy states during grain collisions [3]. Their preliminary model predicts that large grains in the bidisperse mixture charge positively while small grains charge negatively, in agreement with experimental results [4]. However, Lacks and Levandovsky assume that only a single electron is transferred during a collision, regardless of the size of the grains that are colliding. We have allowed the number of electrons transferred during a collision to be proportional to the contact area of the collision. In addition to reproducing the experimentally-observed size dependent charging (where large grains charge positively), our model predicts that for specific mass fractions and relative sizes of the bidisperse mixture (a small mass of small grains), the opposite charge separation will occur (with large grains charging negatively).

Given our model of charge separation in a bidisperse collection of grains, we are

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currently designing an experiment to test our prediction of charge separation as a function of the species sizes and mass fractions as well as to observe the time-varying average charge on each species. We are also in the process of developing a Contact Dynamics numerical simulation to model granular flows, with the goal of simulating landslides or spacecraft-surface interactions. A Contact Dynamics simulation is similar to a Discrete Element Model (DEM) simulation in that the motion of individual grains is simulated. In Contact Dynamics simulations, the time step is constant and grains are not allowed to deform or overlap [5]. Eventually, we plan to include tribocharging in the Contact Dynamics model. This presentation will discuss our tribocharging model, plans to experimentally test our tribocharging predictions, and the current status of our Contact Dynamics simulation, all in the context of using these models to understand the surface environment of small planetary bodies.

[1] P. Sanchez and D. Scheeres, Meteoritics & Planetary Science **49** 5, (2014), pp. 788–811.
[2] C. Hartzell and D. Scheeres, JGR-Planets **118**, (2013), pp. 116–125.
[3] D. Lacks and A. Levandovsky, J. Electrostatics **65**, (2007), pp. 107–112.
[4] K. Forward, D. Lacks and R. Sankaran, PRL **102**, (2009), pp. 028001.
[5] F. Radjaï and V. Richefeu, Mechanics of Materials **41**, (2009), pp. 715-728.

Gonzalo Tancredi **12:05 – 12:25**

Granular media in the context of Small Solar System Bodies

Gonzalo Tancredi,* Andrea Maciel, Sergio Nesmachnow, and Daniel Frascarelli

Depto. Astronomia, Fac. Ciencias, URUGUAY

Granular materials of different sizes are present on the surface and the interior of several atmosphere-less Solar System bodies. Very fine particles are present on the surface of the Moon and many asteroids, the so-called regolith. Larger grains up to the size of boulders have been detected by close-approaching spacecraft.

Solar system bodies smaller than a few hundred km. may have a variety of internal structures: monolithic single bodies, objects with internal fractures, rubble piles maintained as a single object by self-gravity, etc. After the visit of the small asteroid Itokawa, it has been speculated that some small asteroids appear to be clumps of gravel glued by a very weak gravity field. We still do not know the internal structure of these rubble piles and the size distribution of the interior constituents, but these clumps could have several million m-size boulders inside. There are several evidences that many asteroids are agglomerate of small pieces, like: i) rotation periods for small asteroids; ii) tidal disruption of asteroids and comets when they enter the Roche's limit of a massive object; iii) the existence of carter chains like the ones observed in Ganymede; iv) low density estimates (< 2 gr/cm^3) for many asteroids like Mathilde. It has been proposed that several typical processes of granular materials (such as: the size segregation of boulders on Itokawa, the displacement of boulders on Eros, the ejection of dust clouds after impacts) can explain some features observed on these bodies.

The low-gravity space environments are difficult to be reproducible in a ground-based laboratory. Therefore, the numerical simulation is the most promising technique to study the phenomena affecting granular material in vacuum and low-gravity environments. We have presented one of the pioneering paper in the topic: "Granular physics in low-gravity environments"[1]. Hereafter, we present some results of this work as well as some further improvements. One of the numerical experiments is presented in Fig. 63.

Many small solar system bodies, like asteroids and comets, are agglomerates of small objects, maintained together by self-gravity. In order to study the evolution of these bodies under internal and external interactions, a fast method to compute the self-gravity of systems composed by millions of particles is needed.

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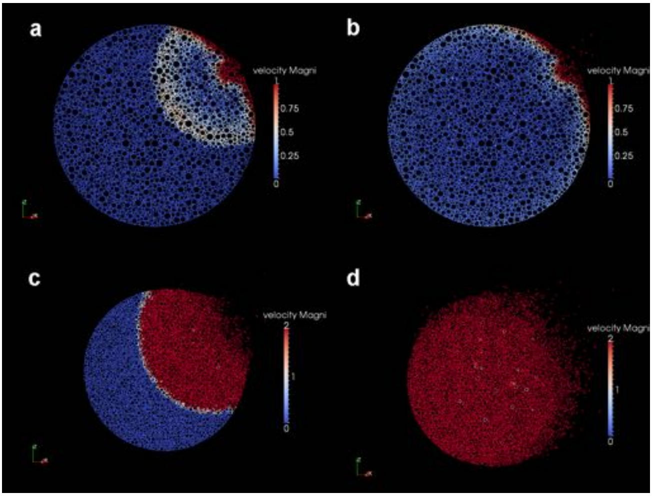
In [2] we present a fully parallel algorithm for self-gravitating aggregates in a dense state, which makes use of a grid to divide space, a hierarchical grouping method to speed the computation in the grid nodes, and an approximation of the exact gravitational potential by an smooth function of the position. We are in the process to incorporate this algorithm into a DEM code to simulate the evolution of agglomerated bodies under self-gravity.

We review the numerical and experimental studies on granular materials with relevance to the understanding of the physical processes on the interior and the surfaces of minor bodies of the Solar System.



Snapshots of the transmission of a surface explosion into a sphere. These are slices passing through the center of the sphere and the explosion point. The two sets of snapshots correspond to different explosion velocities.

[1] Tancredi, G., Maciel, A.,Heredia, L., Richeri, P., Nesmachnow, S.; Granular physics in low-gravity environments using DEM; Monthly Notices of the Royal Astronomical Society, 420, 3368-3380 (2012)

[2] Frascarelli, D.; Nesmachnow, S.; Tancredi, G.; High Performance Computing of Self-gravity for Small Solar System Bodies; IEEE Computer, 47, 34-39; DOI: 10.1109/MC.2014.249 (2014)

Keynote | **Wolfgang Losert** | **14:00 – 14:45**

Convection in 3D granular flows

Wolfgang Losert*

Department of Physics, University of Maryland College Park, College Park, MD, USA

In thermal systems, convective circulatory flows arise from a temperature gradient inducing density fluctuations. Similar patterns of convection are also common in athermal granular flows, despite the absence of thermal fluctuations.

Using a microgravity-modified Taylor-Couette shear cell under the conditions of parabolic flight microgravity, we demonstrate experimentally that secondary, convective-like flows in a sheared granular material are close to zero in microgravity and enhanced under high-gravity conditions, though the primary flow fields are unaffected by gravity. We suggest that gravity tunes the frictional particle-particle and particle-wall interactions, which have been proposed to drive the secondary flow.

Direct imaging of 3D granular flow fields, using a light sheet scanner shown in the attached image, allows us to elucidate the role of convective flows in detail. We find that convective flows are linked to two key properties of granular flows - the propensity of materials to segregate by size under shear, and the onset of irreversible rearrangements in a granular system under shear. We will discuss the implications of these results for the behavior of granular flows in microgravity environments.

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Jens Biele **14:45 – 15:05**

Drivers, requirements and recent projects on interaction of small body regolith with landers, probes and sampling devices - Philae, MASCOT and beyond

Jens Biele,[1,*] Stephan Ulamec,[1] and Franziska Schmidt[2]

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Lander and sampling tools for sample return missions on small bodies of the Solar System (asteroids, comets) are getting into focus of the big space agencies. DLR is presently involved in the Rosetta Lander Philae, in MASCOT (a lander for the Japanese Hayabusa-2 mission, launch 2014/2015, landing 2018/2019), in the proposal for an ESA/NASA Asteroid deflection mission (AIDA-AIM). Furthermore, a sampling device for a comet sample return mission is being developed at DLR. In November 2014, ESA's cornerstone mission Rosetta delivered the comet lander Philae (lead: DLR and CNES) to the surface of comet 67P/Churyumov-Gerasimenko. From this event (and the long-term science phase expected in summer 2015), measurements of the mechanical properties of the comet soil are becoming available as ground truth for verification/validation and calibration of numerical and theoretical models.

Regolith is a granular medium, a layer of loose, heterogeneous material covering solid rock objects in space. It includes dust, soil, broken rock, and other related materials and is present on Earth, the Moon, Mars, some asteroids, and other terrestrial planets and moons. On comets, it may involve aggregates (1cm) of mikrometer-sized silicate and ice grains, leading to an extremly low tensile strength but appreciable compressive strength (aka resistance to penetration). The material on comet 67P was rather harder than expected, more than 1 MPa at places, which may indicate 'sintering' (recondensation of volatiles between the grains). The 'resistance to penetration' of an unsintered coarse regolith layer on a comet is still unclear - the fundamental question is whether the material, being indented by a technical structure, experiences confined compression or whether it is displaced to the sides. MASCOT will land with 0.1m/s on a small asteroid and bounce a number of times; it has an internal torquer for mobility. We are interested in predictions of the coefficients of restitution for this interaction.

DLR is coordinating a joint project (U Tübingen, U Twente, DLR, Obs. Nice) to develop, by numerical simulation, mesoscopic mechanical interaction models for asteroid- and comet-surface materials. The paper will report on preliminary SPH calculations done at the U Tübingen and further simulation plans.

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Christina Knapek 15:05 – 15:25

Complex Plasma Research in Microgravity

C. A. Knapek,[1,*] P. Huber,[1] S. A. Khrapak,[1] A. M. Lipaev,[2] V. I. Molotkov,[2] V. E. Fortov,[2] A. V. Ivlev,[3] G. E. Morfill,[3] and H. M. Thomas[1]

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[2] *Joint Institute for High Temperatures, Moscow, Russia*

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Complex plasmas are considered the soft matter state of plasmas. They are generated by injecting micrometer-sized grains, typically made from plastic, into a low temperature noble gas discharge. Typical ionization fractions of the plasma are low, in the range of 10^{-7}-10^{-8}. As soon as the grains get in contact with the plasma, they get charged by the flows of electrons and ions to their surface. Due to the higher mobility of the electrons the particle charge is usually negative and can reach several thousand elementary charges. The neutral gas component provides a weak damping of the particle motion by friction.

The charged particles interact with each other via a screened Coulomb potential, and can form gaseous, liquid or solid states. Since the particles are individually visible, their atomistic dynamics are virtually undamped and it is possible to generate huge systems with up to 10^9 particles, complex plasmas provide a new experimental approach for fundamental studies of strong coupling phenomena with fully resolved dynamics at the individual particle level.

On ground, gravity compresses the system and prevents the generation of larger, three-dimensional particle clouds. Therefore, research in microgravity conditions, e.g. on parabolic flights, sounding rockets or the International Space Station (ISS) is necessary. Since 2001, complex plasma laboratories are operated on the ISS, starting with PKE-Nefedov (2001-2005), PK-3 Plus (2006-2013) and most recent PK-4 which was launched in 2014.

The research topics include, amongst others, studies of waves, fluid regimes and instabilities in complex plasmas. Here, some recent results of experiments on phase transitions and phase separation, conducted with the PK-3 Plus laboratory (Fig. 63) on board the ISS, will be presented: Phase transitions in three-dimensional complex plasmas, especially the fluid-solid transition observed during freezing and melting of a large particle cloud [1], could be observed and studied on the individual particle level, yielding insights into the underlying processes. Recently, the behavior of binary complex plasmas has been investigated, where particles of different sizes are inserted into the plasma simultaneously.

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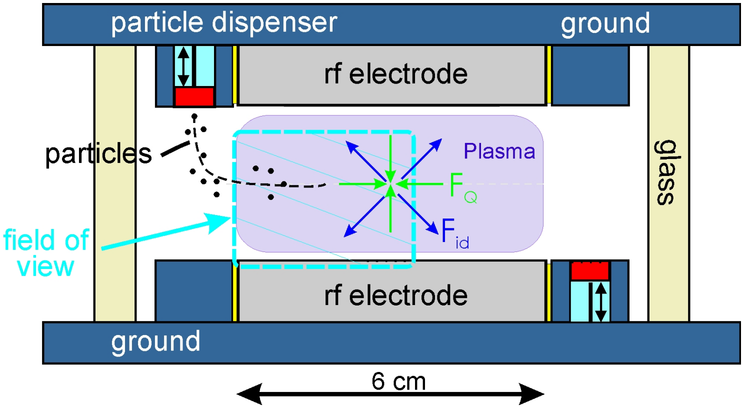
This leads to phase separation [2], similar to the demixing of e.g. water and oil. With complex plasmas, demixing could now be studied on the "atomistic" level for the first time.



The plasma chamber of the PK-3 Plus setup. Plasma is generated between two parallel electrodes by HF-signals to the electrodes. Particles are injected by dispensers build into the grounded guard-rings. The blue and green arrows inside the plasma indicate the confining electrical force and the ion drag force acting outwards on the grains.

ACKNOWLEDGMENTS

This work and some of the authors are funded by DLR/BMWi FKZ 50WP0203, 50WM1203 and 50WM1441.

[1] S. A. Khrapak, B. A. Klumov, P. Huber, V. I. Molotkov, A. M. Lipaev, V. N. Naumkin, H. M. Thomas, A. V. Ivlev, G. E. Morfill, O. F. Petrov, V. E. Fortov, Yu. Malentschenko and S. Volkov, Phys. Rev. Lett. **106**, 205001 (2011).

[2] A. Wysocki, C. Räth, A. V. Ivlev, K. R. Sütterlin, H. M. Thomas, S. Khrapak, S. Zhdanov, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, O. F. Petrov, H. Löwen, and G. E. Morfill, Phys. Rev. Lett. **105**, 045001 (2010).

Keynote **Gerhard Wurm** **16:00 – 16:45**

The Granular Nature of (Pre)-Planetary Environments Studied under Different Gravity Conditions

Gerhard Wurm*

Faculty of Physics, University of Duisburg-Essen

Many settings of astrophysical and planetary context include small particles. Planet formation starts with very small (sub)-micrometer grains, which are very cohesive. Growing to larger aggregates these units sometimes behave more and more like less cohesive granular matter. So the physics of granular matter is important for early stages of planet formation. Considering later stages with existing planetary bodies, i.e. current day planetary surfaces, seemingly similar situations are found e.g. on the surface of Mars and Earth. For both the granular soil provides material transported by wind or dust devils. However, the physical mechanisms working might differ from each other quite a bit due to different environmental settings, the level of gravity being among these.

Being slightly more specific, some fundamental problems to be answered are:

- What are the sticking forces between grains or what is the tensile strength determining the evolution of a granular medium at low gravity?
- How do dominating photophoretic forces or thermal creep influence the fate of a granular gas or granular bed under low gravity?
- Is the environment of protoplanetary disks promoting the formation of larger bodies or are the processes rather destructive?
- How will a dusty / granular body evolve under different conditions?
- What physics determines the particle lift from the martian surface?

These are but a few examples in a wide field where quite a number of parameters can be varied. Important in the context here besides gravity are: insolation, temperature, ambient pressure, gas flow and particle size distributions. In recent years experiments to shed light on different physical mechanisms were carried out in microgravity (zero g), simulated microgravity (using levitation), low gravity (<1g), Earth gravity (1g), and hypergravity (<2g). They studied collisional processes as well as processes occuring in dust beds as sketched in fig. 63 being subject to different stimulation changing the dust bed.

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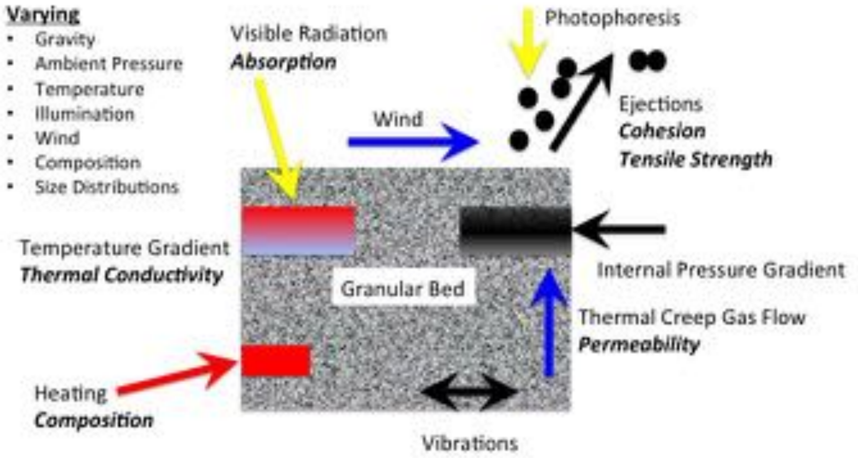
I will present some aspects in more detail, the experiments, the physics behind it and the application to extraterrestrial settings.



Our recent studies of (pre)-planetary surfaces are centered around granular beds with small but significant cohesion. This bed is illuminated, heated and embedded in a low pressure environment. Gas flow through the bed and particle ejections are one major focus.

ACKNOWLEDGMENTS

The projects reported on were supported by the BMWi, DLR, DFG, ESA, and DAAD.

Dearaj van der Meer 16:45 – 17:05

On creating macroscopically identical granular systems with different numbers of particles

Devaraj van der Meer,[1,*] Nicolás Rivas,[2] and Stefan Luding[2]

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[2] *Multi Scale Mechanics (MSM), MESA+, CTW, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands.*

One of the fundamental differences between granular and molecular hydrodynamics is the enormous disparity in the total number of constituents. The small number of particles involved, implies that the role of fluctuations in granular dynamics is of paramount importance. To obtain more insight in these fluctuations, we investigate to what extent it is possible to create identical granular hydrodynamic states with different number of particles. A definition is given of macroscopically equivalent systems, and the dependency of the conservation equations on the particle size is studied. We show that, in certain cases, and by appropriately scaling the microscopic variables, we are able to compare systems with significantly different number of particles that present the same macroscopic phenomenology. We apply these scalings in simulations of a vertically vibrated system, namely the density-inverted granular Leidenfrost state [1, 2] and its transition to a buoyancy-driven convective state [3].

[1] B. Meerson, T. Pöschel, and Y. Bromberg, Phys. Rev. Lett. **91**, 024301 (2003).

[2] P. Eshuis, K. van der Weele, D. van der Meer, and D. Lohse, Phys. Rev. Lett. **95**, 258001 (2005).

[3] P. Eshuis, D. van der Meer, M. Alam, H.J. van Gerner, K. van der Weele, and D. Lohse, Phys. Rev. Lett. **104**, 038001 (2010).

[4] N. Rivas, S. Luding, A.R. Thornton, New J. Phys. **15**, 113043 (2013).

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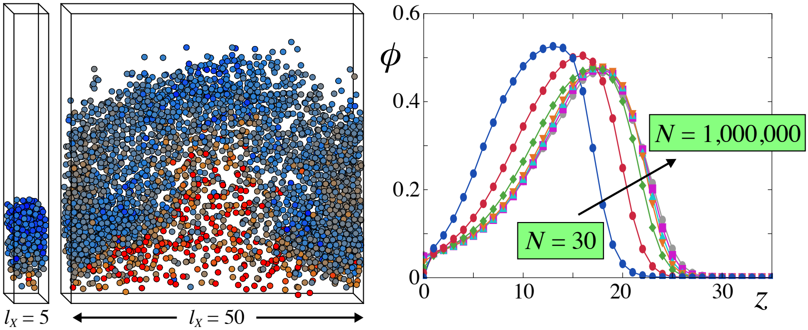


Snapshots from a simulation showing the Leidenfrost (left) and buoyancy-driven convective states (middle) in a vertically driven quasi-twodimensional system of varying width, under the same shaking conditions [4]. On the right, and again under the same conditions, the packing fraction ϕ is plotted as a function of height z for different numbers of particles per unit area N, ranging from $N = 30$ to $N = 1,000,000$. Clearly, $\phi(z)$ quickly converges to a profile that is independent of particle number.

Poster Contributions

Posters are displayed for the duration of the conference. There is a dedicated **Poster Session** on Wednesday from 6:30pm to 10:00pm.

Please take note of the "People's Choice Best Poster Award". Your registration bag contains a ballot slip for your choice of the three best posters. Each poster can be identified by its number on the poster board. Note that you can only vote once for each poster. Please hand in your completed ballot slip by Friday's lunch break. The winners will be announced at close of the last session on Friday afternoon.

Poster 1 **Lydia Almazan**

Sedimentation of a granular gas for different gravities

Lídia Almazán,[1,*] Dan Serero,[1] Thosten Pöschel,[1] and Clara Salueña[2]

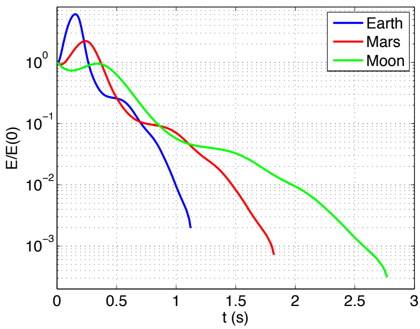
[1] *Institute for Multiscale Simulation, Engineering Advanced Material, Friedrich-Alexander-Universität Erlangen-Nürnberg*

[2] *Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili*

Granular gases under gravity need external support of energy to balance the loss of energy due to dissipative collisions, otherwise they would quickly come to rest, as gravity favours dense packing in which energy is rapidly dissipated. Using numerical hydrodynamic analysis for inelastic hard disks we study the sedimentation until collapse on Earth, Mars and Moon. A wide study on Earth has been done in Almazán et.al. [1], where we compared different initial conditions of the system and different coefficients of restitution of the granular material.

During the process of sedimentation, we observed several stages which reveal distinct spatial regions of diffusive and inertial behaviour. During this process, self-organized shocks appear, accompanied by sharp profiles of the hydrodynamic fields of temperature and density.

The second part of the study is the collapse, the last stage of the sedimentation. As we can see in Fig. 63, the decay of energy of the granular material depend on gravity, losing energy faster when the gravity is higher.



This figure shows the energy decay along the time for different gravities, when we leave without an external force a granular gas under the action of gravity.

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ACKNOWLEDGMENTS

We thank DFG for funding through its Cluster of Excellence Engineering of Advanced Materials.

[1] L. Almazán, D. Serero, C. Salueña and T. Pöschel, *Self-organized Shocks in the Sedimentation of a Granular Gas*, Submitted.

Poster 2 **Anna Bodrova**

Nonergodic dynamics of force-free granular gases

Anna Bodrova,[1,2,*] Aleksei Chechkin,[2,3] and Ralf Metzler[2,4]

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Ergodicity is a fundamental concept of statistical mechanics. Starting with Boltzmann, the ergodic hypothesis states that long time averages of physical observables are identical to their ensemble averages. In the wake of modern microscopic techniques such as single particle tracking, in which individual trajectories of single molecules or submicron tracers are routinely measured, knowledge of the ergodic properties of the system is again pressing: while time averages are measured in single particle assays or massive simulations, generally ensemble averages are more accessible theoretically. How measured time averages can be interpreted in terms of ensemble approaches and diffusion models is thus imminent [1].

Here we demonstrate in quantitative detail how ergodicity is violated even in simple mechanical systems such as force-free granular gases [2]. We analytically derive the time and ensemble averaged mean squared displacements (MSDs) and show that for both constant and viscoelastic restitution coefficients the time average of the MSD is fundamentally different from the corresponding ensemble MSD (Fig. 29). Moreover, the amplitude of the time averaged MSD is shown to be a decaying function of the length of the measured trajectory (aging). Comparison to the effective single particle underdamped scaled Brownian motion demonstrates that this behavior is due to the non-stationarity invoked by the time dependence of the granular temperature. Our results for generic granular gases are relevant both from a fundamental statistical mechanical point of view and for the practical analysis of time series of granular gas particles from observations (in particular, of granular gases in Space) and simulations.

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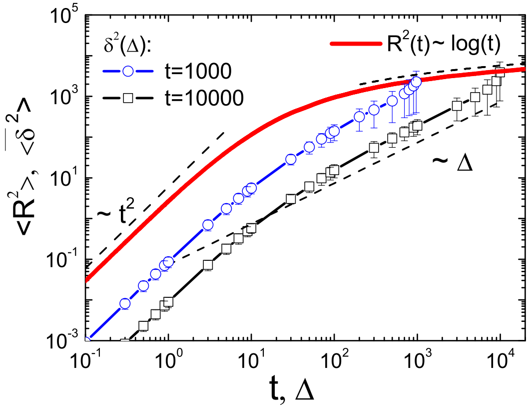

Ensemble $\langle R^2(t)\rangle$ and time averaged $\langle\overline{\delta^2(\Delta)}\rangle$ MSDs versus (lag) time from event-driven MD simulations of a granular gas with $\varepsilon = 0.8$ (symbols). While the ensemble MSD crosses over from ballistic motion $\left\langle R^2(t)\right\rangle \sim t^2$ for $t \ll \tau_0$ to the logarithmic law $\left\langle R^2(t)\right\rangle \sim \log(t)$ for $t \gg \tau_0$, the time averaged MSD starts ballistically and crosses over to the scaling $\langle\overline{\delta^2(\Delta)}\rangle \sim \Delta/t$

ACKNOWLEDGMENTS

This work was supported by EU IRSES DCP-PhysBio N269139 project

[1] R. Metzler, J.-H. Jeon, A. G. Cherstvy, and E. Barkai, Phys. Chem. Chem. Phys. **16**, 24128 (2014).

[2] A. Bodrova, A.V. Chechkin, A.G. Cherstvy, R. Metzler. Nonergodic dynamics of force-free granular gases. http://arxiv.org/abs/1501.04173

Poster 3 **Alexander Börngen**

PlasmaLab / EKOPlasma – The upcoming Experiment for Complex Plasma Research on the ISS

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EKOPlasma is planned as the successor of the PK-4 experiment and will be the future of complex plasma research on the ISS. Complex plasmas generated in the laboratory consist of ionized gas (mainly noble gas) mixed with micron-sized plastic particles. Due to electrical charging the particles levitate in the plasma and build up different formations from crystalline structures to liquid-like behavior. EKOPlasma is a Russian-German-Cooperation and will base on the "Zyflex" - plasma chamber developed within the scope of the PlasmaLab Project.

The "Zyflex" chamber (Fig. 30) has a cylindrical shape and will become so far the largest plasma chamber for complex plasma research in space. The electrodes as well as the guard rings are movable independently to vary the distance (plasma volume). Furthermore the design allows a huge extension of the accessible plasma parameters like plasma density and electron temperature. Due to this the experimental quality and the expected knowledge gain will increase significantly.

Additionally the setup reaches low neutral gas pressure which means weak damping of particle motion and allows the generation of large, homogeneous 3D particle systems to study fundamental phenomena such as phase transitions, dynamics of liquids or phase separation.

For the 3D observation of the particles two different camera systems are under testing. One system (Raytrix) uses a Plenoptic Camera, the other system use three cameras placed in different solid angles.

A current status of the work will be shown on the poster. It will present the two camera systems tested for the 3D observation of the particles, the system to store different kinds of dust/particles as well as some other systems used for the plasma manipulation and analysis which are currently under development. Information about the project schedule will be given too.

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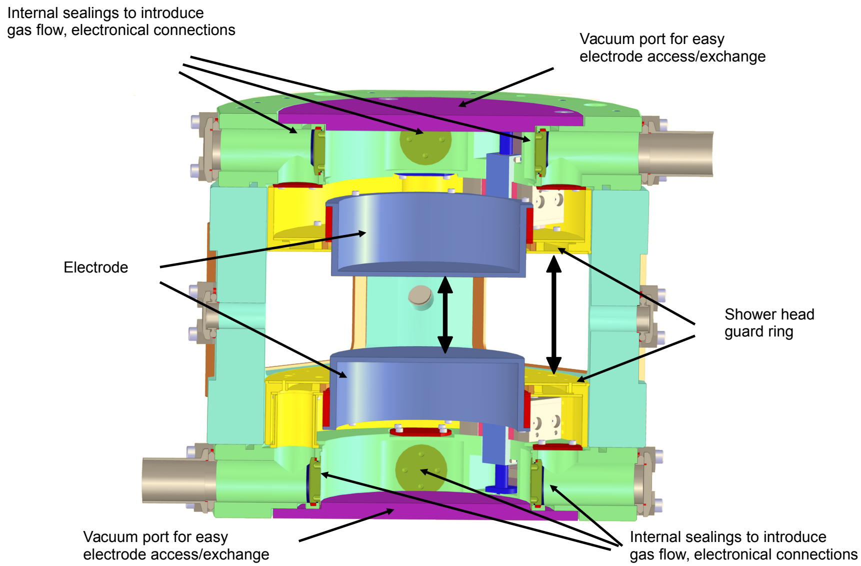

"Zyflex" plasma chamber in cross section view: The cylindrical shaped plasma chamber shall become the biggest one ever used in space before. Upper and lower electrodes as well as the corresponding guard rings are moveable independently to each other. The cross section shows the current plasma chamber used for experiments in the laboratory and during parabola flights. Here the electrodes can be exchanged easily to test different kinds of electrodes like grid electrode, electrodes with heating / cooling elements for temperature control and electrodes with two different RF sections with independent RF control.

ACKNOWLEDGMENTS

This work and some of the authors are funded by DLR/BMWi (FKZ 50WM1441).

Poster 4 **Qiong Chen**

Granular Phase Separation in Microgravity (poster)

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Granular phase-separation is studied in microgravity through the drop tower experiment. Monodisperse titanium particles in five cells of same width (50mm) and depth (10mm) with different lengths Lx 150/120/100/50/30mm are shaken by a motor with frequency of 5Hz and amplitude of 13mm horizontally. Titanium particles of diameters $d = 2.5$mm, 1mm, and 0.5mm are used. Following results of our previous event-driven molecular dynamics simulations and hydrodynamic calculations for the phase separation [1] [2] [3] [4], the spinodal areas of particle number N vs. the cell length Lx are plotted for different particle coefficients of restitution e in Figure 63. The numbers and sizes of titanium particles in different cells are shown in Figure 64(a) and 65(a). Particles are agitated in low-gravity for about 3.5 seconds during the free fall of 60 meters. Patterns of two experimental runs are shown in Figure 64(b) and 65(b). In Fig. 64 for size-2.5mm particles cluster is seen only for $N = 500$ and Lx=150mm cell. Clusterings at the middle of the cells are seen in almost of all the cases in Fig. 65. The results show that the particle coefficient of restitution shall be higher than 0.8, which helps us in determining the number of particles in the SJ-10 satellite experiment.

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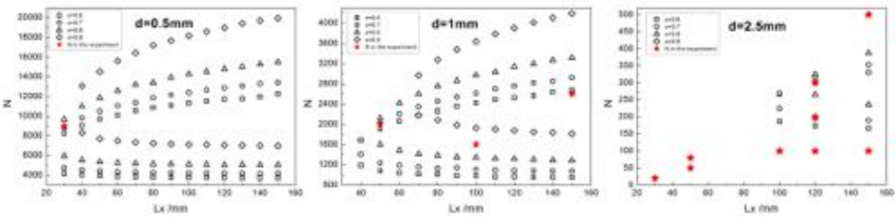
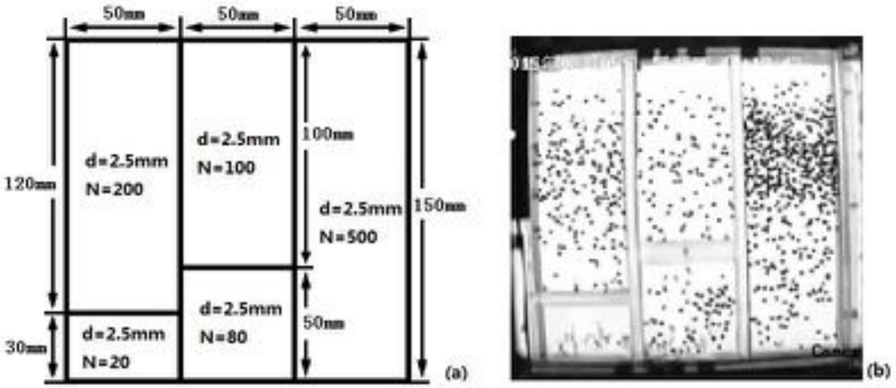


Phase diagrams of particles numbers N vs. the cell lengths Lx for different coefficients of restitution are plotted for particles diameter (a)0.5mm, (b)1mm, and (c)2.5mm. Red stars are experimentally chosen sets of (N, Lx)

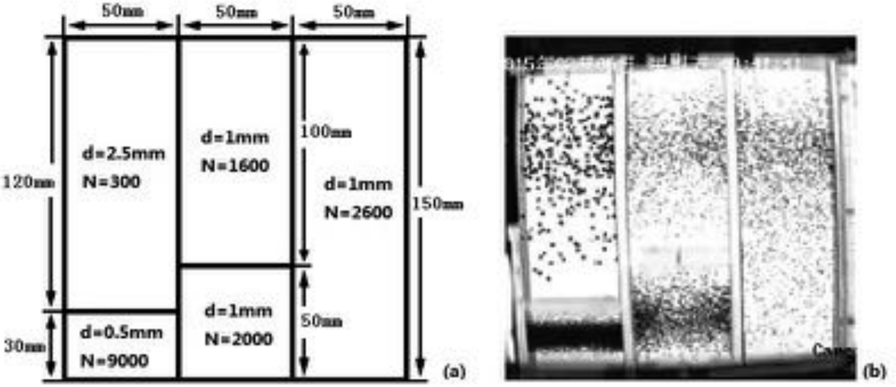


set one:(a) Numbers and sizes of titanium particles in different cells, (b) Snapshot of the distribution pattern.

ACKNOWLEDGMENTS

This work is supported by the Key Program of the National Natural Science Foundation of China (Grant No. 11034010), the National Natural Science Foundation of China (Grant No. 11274354, 11474326), the Special Fund for Earthquake Research of China (Grant No. 201208011), and the Strategic Priority Research Program-SJ-10 of the Chinese Academy of Sciences (Grant No. XDA04020200).

[1] R. Liu, Y. Li, M. Hou and B. Meerson, Phys. Rev. E **75**, 061304 (2007).
[2] R. Liu, Y. Li and M. Hou, Acta Phys. Sin. **57**, 4660 (2008).



set two:(a) Numbers and sizes of titanium particles in different cells, (b) Snapshot of the distribution pattern.

[3] M. Hou and R. Liu, Chin. J. Space Sci. **28**, 1 (2008).
[4] E. Opsomer, F. Ludewig and N. Vandewalle, private communication.

A Hyperelasticity Interpretation for Shear Wave and Small Cyclic Tests of Ham River Sand

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Taking the hyperelastic stress-strain relationship in a particular soil constitutive model as an example, this study here presents an approach of calibrating the model using existing data from shear wave and small cyclic tests of granular matters, which in turn provides a new way of interpreting the test results.
Mechanical properties of soils, a typical type of granular matters, are of great importance in the design and safety control of geotechnical engineering. Thus soil constitutive models based on different theories (elasto- plasticity, hypoelasticity, hyperelasticity, etc.) have been developed aiming at replicating soil behaviour under loading. Existing soil hyperelastic constitutive models are mainly calibrated using traditional triaxial tests data. This calibration method has an intrinsic drawback in determining soil elastic parameters, as soils hardly stay elastic while the test is being conducted.
This study here presents an approach of linking soil hyperelasticity stress-strain relationship with shear wave and small cyclic tests of granular matters. The elastic energy function of a newly developed soil constitutive model Tsinghua Thermodynamic Model (TTM) [1] is taken as the research objective. First, the elastic incremental stress-strain relationship of soils was deduced where the incremental stress was obtained by multiplying the elastic incremental strain with a compliance tensor containing parameters that needed to be determined. Second, existing data from shear wave tests done on Ham River sand by Kuwana and Jardine [2] was used to calculate soil elastic moduli. Third, the compliance tensor was linked to the elastic moduli of soils and the parameters were calibrated. The calibrated soil hyperelastic stress-strain relationship was verified and evaluated against experimental data.
The calibrated energy function showed the ability of capturing essential soil characteristics and it also yielded results in accordance with experimental data within an acceptable error margin, which indicated that it is feasible and appropriate to interpret shear wave and small cyclic tests of granular matters from a hyperelasticity point of view.

[1] Z.C. Zhang, X. H. Cheng, Int. J. Numer. Anal. Met. (Submitted)
[2] R. Kuwano, R. J. Jardine, Geotechnique, **52**, 727 (2002).

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Poster 6 **Johannes Deckers**

Collisions of Decimetre Dust

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Decimetre bodies and their collision dynamics are important for the different models for the growth of km-sized objects, the planetesimals. Planets are formed by accretion of these planetesimals. The processes involved in the growth of the planetesimals are not understood in detail, yet.
In order to investigate collision properties of decimetre dust, we performed collision experiments with dust agglomerates consisting of μm quartz grains that have porosities of about 55%.
In collisions of dust agglomerates of different sizes we observe mass transfer from the smaller to the larger body (Deckers and Teiser 2014). We find a grown structure in the form of a cone sticking to the dm body (see Fig. 1), just like formed by a jet of granular matter impacting a solid target of equal diameter (Cheng et al. 2007). This suggests a transition from material bound by cohesion forces to a granular matter like behaviour.
In mutual collisions of dm agglomerates in microgravity we analysed the threshold between bouncing and fragmentation (Deckers and Teiser 2013). In addition to that, in laboratory experiments we found the threshold to catastrophic disruption is at 190 J kg^{-1}, a factor 4 larger than expected (Deckers and Teiser 2014). Both results show that the impact disruption of dm bodies is dominated by material strength, but lies close to the regime where gravity becomes important (Beitz et al. 2011, Benz and Asphaug 1999).

ACKNOWLEDGMENTS

This work is funded by the "Deutsche Forschungsgemeinschaft"(DFG) within the SPP 1385 "The First 10 Million Years of the Solar System - A Planetary Materials Approach".

[1] J. Deckers and J. Teiser, "Macroscopic Dust in Protoplanetary Disks - From Growth to Destruction", ApJ 796, 2014

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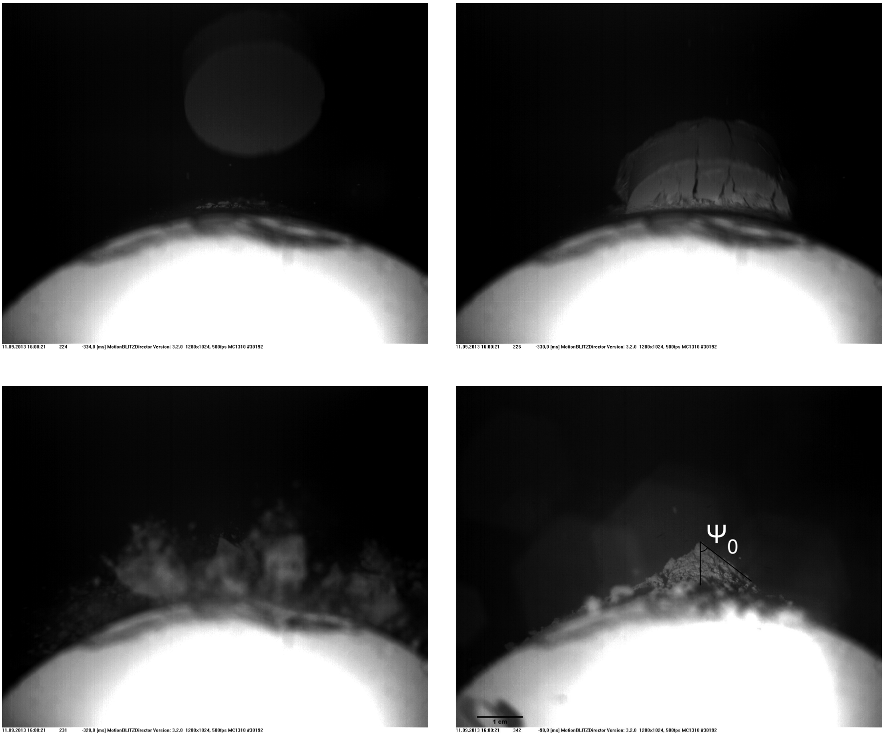

Collision with mass transfer in form of a dust cone

[2] X. Cheng, G. Varas, D. Citron, H. M. Jaeger and S. R. Nagel, "Collective behavior in a granular jet: Emergence of a liquid with zero surface-tension", Phys. Rev. Lett. 99, (2007)
[3] J. Deckers and J. Teiser, "Colliding Decimeter Dust", ApJ 769, 2013
[4] E. Beitz, C. Güttler, J. Blum, T. Meisner, J. Teiser, G. Wurm, "Low-Velocity Collisions of Centimeter-Sized Dust Aggregates", ApJ 736, 2011
[5] W. Benz and E. Asphaug, "Catastrophic Disruptions Revisited", Icarus 142, 1999

Poster 7 **Subodh Dhakal**

Observations of Multi-particle Interactions in Transitional Granular Shear Flows

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Numerical simulations and theoretical studies have been the dominant study approaches in the field of mechanics of granular flows because of the difficulty in getting grain-scale information from the physical experiments. These studies rely mostly on one of the two approaches: Bagnold's approach [1] and the kinetic theory model [3]. Bagnold's approach assumes that the force developed between particles is through instantaneous momentum transfer from particle-particle collisions, and it is responsible for internal stresses. Kinetic theory models are based on an analogy between the fluctuating nature of rapid granular motion and the random molecular motion within a dense gas. One of the major drawbacks of such theoretical models is that collision time is considered negligible, and stresses are supposed to arise solely from binary collisions. This condition cannot be generalized to all types of granular flows, especially in cases where the solid fraction is moderate to dense.

Though similar thoughts have been put forward by many researchers in the past, very few workers tried to verify them with experimental or theoretical results. Therefore, more experimental work is expected to judge whether the available theoretical models can be applied to a moderately dense to dense flow. Additionally, past studies were focused mostly on the quasi-static regime, and the inertia-dominant flow regime despite the fact that most granular flows are neither purely quasi-static nor purely inertia-dominant; rather, they are of transitional type. This is still most challenging regime of granular flow because of the lack of explicit coverage of this regime in the past. In this context, moderately to densely packed assembly of disk particles were sheared in a 2D annular shear flow apparatus by applying a fairly high shear rate to understand the phenomena of multiple collisions in transitional granular flow. High speed video camera and subsequent image processing techniques help to document the positions of the center of particles in the flow. More effective collision detection algorithm was formulated to determine the inter-particle collisions at each time step [2]. The flow status was determined in terms of binary and multiple collisions. The results depict that for the range of shear flows investigated in this study, the proportion of multi-particle collisions is considerable (Fig. 1), and the inter-particle collision

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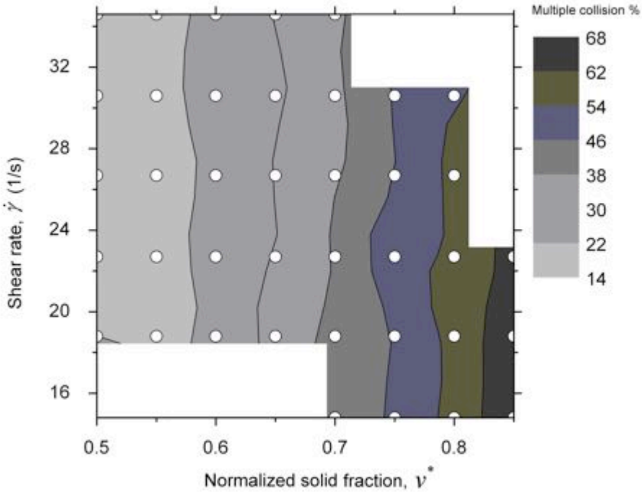
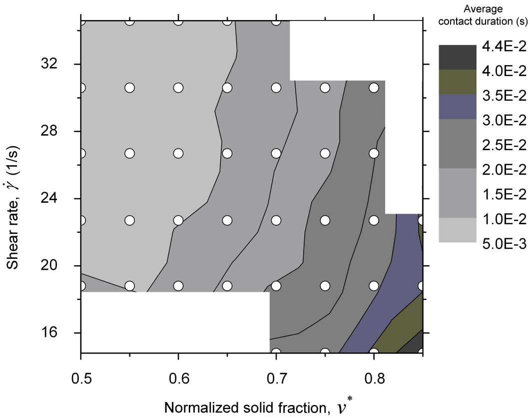
time is greater than the binary collision time even in the lowest solid fraction case (Fig. 2).



Contour plot of multiple collision percentage against solid fraction and shear rate. The white circles denote points where data were measured. The bottom left and top right portions of the plot area are masked as they are not covered by present experimental apparatus.

The group size is determined as an additional length scale associated with multi-particle interactions that becomes irrelevant under binary collision conditions. Quite a number of groups are found to consist of more than two particles in all the flows under consideration, and the amount of such group increases on increasing solid fraction regardless of the shear rate. The change in the stress generation pattern is observed in the dense cases with solid fraction greater than 0.60 where there is a rapid increase in the multiple collisions, group size and the occasional force chains. These observations therefore imply that the shear stress generation pattern differs from the existing models like that obtained from the kinetic theory of gases for transitional granular flows if the shear deformation rates are not so small.

[1] R. A. Bagnold, Proc. R. Soc. London, **A 225**, 49-63 (1954).
[2] S. Dhakal, K. Iwashita, M. Oda, Journal of Applied Mechanics, JSCE, **11**, 477-486 (2008).



Contour plot of average contact duration in seconds against solid fraction and shear rate. The white circles denote points where data were measured. The bottom left and top right portions of the plot area are masked as they are not covered by present experimental apparatus.

[3] S. B. Savage, D. J. Jeffrey, J. Fluid Mech. **110**, 255-272 (1981)

Poster 8 **Claudia Faber**

Travel times of elastic waves in porous layered cometary surface material

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Travel times of elastic waves can be used for the determination of mechanical properties of a medium. For example, material parameters describing the elastic properties are, among others, the Young's modulus E and the Poisson's ratio ν. For a homogeneous material they are given by

$$E = \rho c_S^2 \frac{4c_S^2 - 3c_P^2}{c_S^2 - c_P^2}$$

and

$$\nu = \frac{1/2 - (c_S/c_P)^2}{1 - (c_S/c_P)^2},$$

where c_P and c_S are the propagation velocities of longitudinal and shear waves, respectively, and ρ is the mass density.

If there is a porous material in a low gravity environment, like it is the case for comet surfaces for example, the pores are empty or filled at a low pressure. Such pores are efficient reflectors for elastic waves, so multiple scattering occurs, which causes a much more complex wave field compared to non-porous material. In [1] it was suggested that a depleted porous crust covered by a stable dust mantle may has formed on comet nuclei. Because of recondensation, there is a higher ice density and a lower porosity beneath the crust-core interface than in the crust. In this case additional refraction at the layer boundary (head waves) may be observed. Thus, the identification of arrival times and hence the determination of E and ν is a complex issue.

Here, seismic sections obtained from two dimensional EFIT (Elastodynamic Finite Integration Technique) [2] forward modelling are presented. According to

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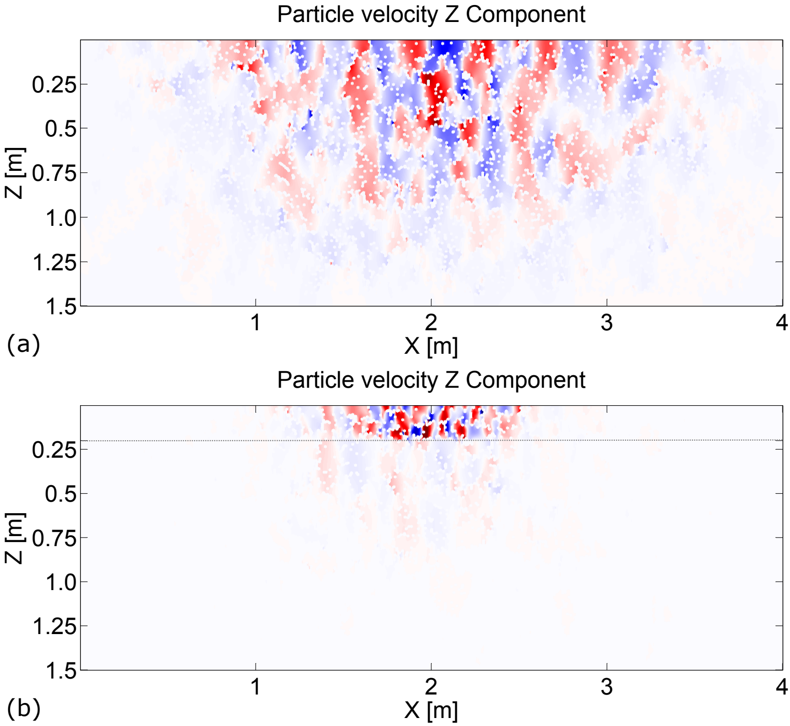
the SESAME-CASSE experiment of the Rosetta mission, a point source with a signal frequency in the kHz range [3] is implemented. A comparison of different material models in terms of pore sizes/grain sizes and porosities is shown. The seismograms are investigated regarding whether it is possible to distinguish longitudinal from shear waves and to observe head waves. The latter might be used for deriving the layer depth. Furthermore it is investigated how the attenuation correlates with porosity and pore sizes.



Snapshots of particle velocity Z component (colour coded) in a porous medium, (a) without a layer boundary, (b) with a layer boundary at Z = 0.2 m. A point source is located at X = 2 m, Y = 0 m. Positive values of the velocity are indicated by red colour, negative values by blue colour.

[1] E. Kührt and H. U. Keller, Icarus **109**, 121-132 (1994).
[2] P. Fellinger et al., Wave Motion **21**, 47-66 (1995).
[3] K. J. Seidensticker et al., Space. Sci. Rev. **128**, 301-337 (2007).

Poster 9 **Nina Gunkelmann**

Granular mechanics of porous clusters: compaction and fragmentation

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The study of collisions of granular materials is ubiquitous in astrophysics and the dynamic behavior of impacts of large projectiles was intensely studied in the past [1]. However, the universe contains a large number of dust grains with micrometer sizes which play an important role in the field of planetary science. For instance, the evolution of interplanetary dust clouds is the first stage of planet formation. It catalyzes the formation of molecules which determine the possible cooling and collapse of clouds into stars and planetary systems. There are many investigations of the convergence of colliding dust agglomerates in laboratory experiments. However, experiments are often not able to realize the ambient conditions in space environment.

In this work, we study collisions between small aggregates of dust grains as well as impacts of spheres into porous granular targets using molecular dynamics simulations. Collisions between granular clusters provide energy for desorbing molecules which might exist on the surface, generate energy to jump chemical reactions and change the porosity of the clusters affecting the surface of the porous clusters available for catalysis. Depending on the particles size and the impact parameters our results reveal a complex set of outcomes from sticking to partial or full destruction of the clusters [2]. We find good agreement between our results and analytical models at atomistic and continuum scale. We study also collision-induced compaction and show that large clusters result in considerably higher compactions at higher velocities. Collision-induced compaction is seen to be strongly inhomogeneous.

The latter coincides with our results on impacts into porous targets where the excavated craters of conical shape are surrounded by compaction zones which strongly depend on the target density [3]. It can be found out that the projectile

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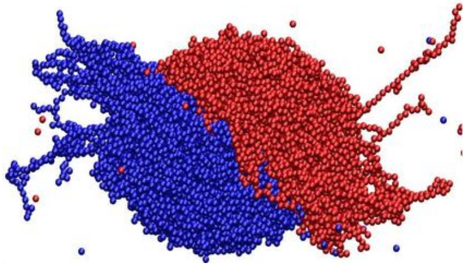
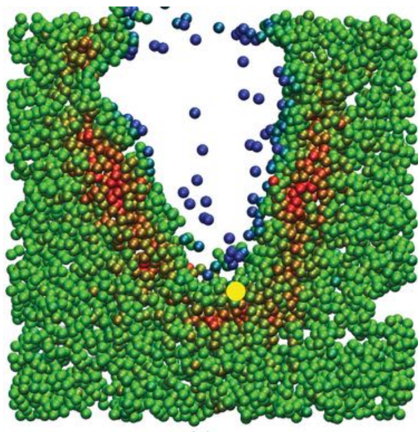


Final snapshot of a typical collision event showing agglomeration.

is stopped by an effective drag force which is proportional to the square of its velocity. The penetration depth depends approximately logarithmically on the impact velocity, and is inversely proportional to the target density.



Snapshot of a crater caused by the impact of a projectile into a target. Color code denotes relative target compaction.

[1] H. J. Melosh, *Impact Cratering: A Geological Process* (Oxford Univ. Press, New York, 1989).
[2] C. Ringl et al., Astrophys. J. **752**, 151 (2012).
[3] C. Ringl et al., Phys. Rev E **86**, 061313 (2012).

Poster 10 **Kirsten Harth**

Impact of the microgravity platform on the preparation and spatial properties of 3D granular gases

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Granular gases are dilute ensembles of at least millimeter-sized grains, undergoing an erratic motion and collisions of particles, which on a first glance resemble our simplest picture of molecular gases. However, their particle collisions are dissipative by nature. They give a vivid example of a dynamic ensemble of particles with random interactions, therefore granular gases are often considered as a simple model systems to investigate statistical dynamics far from thermal equilibrium. Immense efforts have been focussed on analytical and numerical modeling of such systems. Experiments with granular gases do not only provide statistical information on multi-particle systems undergoing random dissipative interactions, they may also help to test predictions of numerical simulations and to gain understanding of the self-organization of dilute granular matter to clusters and stable assemblies. However, experiments were so far mainly restricted to flat geometries, small ensemble sizes and/or strong external excitation.

Larger, three-dimensional granular ensembles at low excitation strength can only be prepared in microgravity. First experiments were performed by Falcon et al. [1] with brass spheres at comparatively high filling fractions and excitation. A statistical analysis on the particle was not possible in that study, but dynamical clustering was observed in the raw data.

We have recently started research on granular gases of elongated grains, which possess a number of advantages over gases of spheres. These systems allow a statistical analysis on the particle level far beyond the Knudsen regime [2, 3]. Grain distributions, velocity and rotational velocity statistics and their temporal dependencies become accessible with appropriate preparation. In this contribution, we focus on general spatial properties of these granular gases, homogeneity and randomness.

We evaluate general experimental requirements, evaluate preparation protocols and judge the appropriateness of the different platforms (drop towers, parabolic flight, orbital platforms) for the preparation of such weakly excited systems. We

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will present quantitative results on spatial properties of our granular gases of elongated grains.

We acknowlegde the German Aeropace Center (Grants 50WM1241 and 50WB1344) and German Science Foundation DFG (Grant STA-425/36) for funding. Part of the drop tower experiments were performed within ESA's *Drop Your Thesis!* programme, project GAGa DropT. The sounding rocket flight was performed within the REXUS program (project GAGa) of DLR, ESA and SNSB; we thank U. Kornek, U. Strachauer, S. Höme and K. Will for their contributions.

[1] E. Falcon, R. Wunenburger, P. Evesque, S. Fauve, C. Chabot, Y. Garrabos, and D. Beysens, Phys. Rev. Lett., **83**, 440 (1999). E. Falcon, S. Aumaitre, P. Evesque, F. Palencia, C. Lecoutre-Chabot, S. Fauve, D. Beysens, and Y. Garrabos, Europhys. Lett., **74**, 830 (2006).

[2] K. Harth, U. Kornek, T. Trittel, U. Strachauer, S. Höme, K. Will, and R. Stannarius, Phys. Rev. Lett., **110**,144102 (2013).

[3] K. Harth, T. Trittel, U. Kornek, S. Höme, K. Will, U. Strachauer, and R. Stannarius, AIP Conf. Proc. (Powders and Grains), **1542**, 807 (2013).

[4] K. Harth, T. Trittel, K. May, S. Wegner, and R. Stannarius, Adv. Space Res., DOI: 10.1016/j.asr.2015.01.027 (2015).

Poster 11 **Michael Heckel**

Granular dampers in Microgravity

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We performed experiments on granular dampers for a large abundance of parameters under the conditions of microgravity in a parabolic flight. In order to meet the special requirements of a parabolic flight we built a setup to perform 16 individual experiments synchronously (see the Figure (left)). Their parameters can be adjusted rapidly in the breaks between parabolas by exchanging the individual damper or the entire spring-damper system.

We confirmed that the damping efficiency is independent of the frequency but depends only on the amplitude of the vibration and the clearance in the container. For an example for one damper geometry and different spring constants see the Figure (right). Further we find quantitative agreement with the model prediction [1, 2] for all sets of parameters validating the models remarkably simple assumptions. This agreement includes cases where the applicability of the model may be questioned because of a very small number of particles. Although showing a significant scatter, on average the model still seems to hold true.

In conclusion, based on the large set of data presented in this paper, we confirm the validity of the single particle model in describing the physics of granular dampers.

ACKNOWLEDGMENTS

The European Space Agency (ESA) and the German Aerospace Center (DLR) are gratefully acknowledged for funding the parabolic flights. We thank the German Science Foundation (DFG) for support through the Cluster of Excellence Engineering of Advanced Materials.

[1] J. E. Kollmer, A. Sack, M. Heckel, and T. Pöschel. New J. Phys., **15** 093023 (2013).
[2] A. Sack, M. Heckel, J. E. Kollmer, F. Zimber, and T. Pöschel. Phys. Rev. Lett., **111** 018001 (2013).

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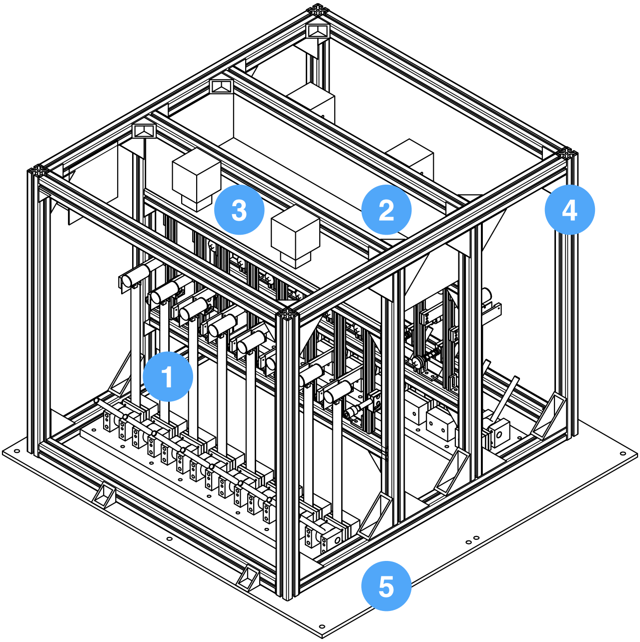

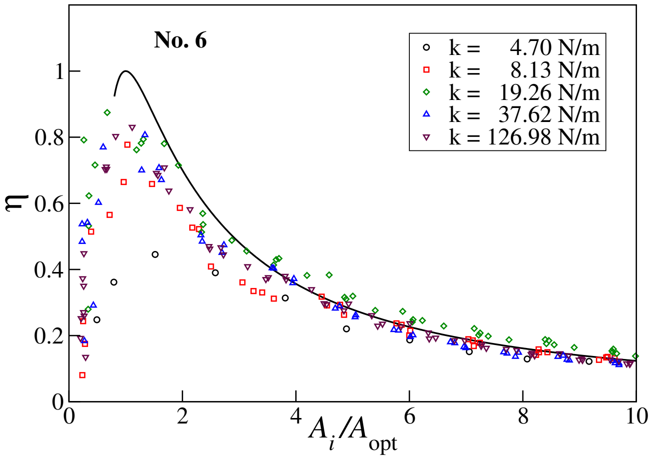

Left: Sketch of the fully assembled experimental rack: (1) two banks of eight oscillators and corresponding electromagnets, (2) storage for additional samples, (3) four cameras for documentation. The experiment is enclosed by an aluminium frame (4) holding polycarbonate panels (not shown) to contain accidental spills and is mounted onto a base plate (5). Right: Damper efficiency η as a function of normalized amplitude A_i/A_opt for sample No. 6 (sphere diameter 4 mm, container length 40 mm, gap size 9 mm, filling mass 25 g) and different spring constants k. The solid black line is the theoretical efficiency resulting from our model.

Poster 12 **Marc Hofmann**

Small scale impacts as trigger for an avalanche in a low gravity environment

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The European Space Agency's Rosetta spacecraft was launched in 2004 and will rendezvous with comet 67P/Churyumov-Gerasimenko in 2014. On its route towards the comet, it flew by asteroid (21) Lutetia on 10 July 2010, with a closest approach distance of 3170 km. OSIRIS - the Optical, Spectroscopic, and Infrared Remote Imaging System on board Rosetta [1] - took 462 images of Lutetia, using 21 broad- and narrowband filters covering a wavelength range from 240 to 1000 nm [2].

The surface of (21) Lutetia is is covered with a thick layer of regolith. On slopes of several craters this regolith layer collapsed in landslide-like events. [3]. A possible trigger mechanism for these low-gravity avalanches is the slow impact of a small mm to cm-sized body

We conducted an experiment where samples of different granular materials were tilted at different angles with respect to the vector of gravity. We accelerated a small mm-sized metal sphere to velocities up to 1.5 m/s and shot it into the sloped granular material. The impacts and any events triggered by the impact were recorded using a high-speed high-resolution camera.

The experiment was implemented at the center of applied space technology and microgravity (ZARM) vacuum drop tower in Bremen in August 2012. The experiment was placed in an evacuated cylinder and mounted on a centrifuge that was spun with varying rotation rates to accommodate the vacuum and low gravity present on the surfaces of asteroids.

A total of 20 experiments as described above were realized during 10 drops. The tilt angle and the magnitude of artificial gravity were varied for two different materials, a ground HED meteorite and the JSC MARS-1 Martian soil simulant [4]. Additional ground-based experiments in 1g environment were conducted at a later time.

We analyzed the images using an image subtraction algorithm to track movement from one frame to the next. In subsequent steps we observed the behavior of the

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material on the surface as well as in deeper layers to characterize the effects of the impact with changing gravitational acceleration, impactor velocity and tilt angle of the material.

The analysis of the experimental data indicates that small scale impacts can, under certain conditions, trigger avalanches in both normal and reduced gravity. The probability to induce an avalanche in the MARS-1 material is lower for coarser sievings.

To gain a better understanding of the microphysical processes governing the distribution of energy in low-energy impacts, a suite of simulations was performed, using a ***D**iscrete **E**lement **M**ethod* (DEM) software called *ESyS-Particle* [5]. DEM codes simulate granular systems by creating an ensemble of spherical particles that interact with external forces and with one another. The experiments described above were recreated within the program in a reduced size to make the calculations less computationally demanding.

The results show that energy introduced into the target material by the impactor is largely retained at the surface of the target. The energy gets dissipated in inelastic collisions that happen more frequently in the depth of the material where the mean number of contacts per particle is higher than at the surface. The energy retained at the surface gets distributed radially away from the impact site. This distribution can be governed by gravity (when g is large) or the local arrangement of the particles (when gravity is low).

These findings reinforce the conclusion that low-energy impacts are a viable trigger mechanism for avalanches of asteroidal regolith, both in low and normal gravity.

Like asteroids, comets retain a dust mantle of varying grain size and thickness. Rosetta's target comet 67P is partly covered with a dust layer [6] that shows evidence for mass wasting [7]. The conditions under which these occur are the focus of our current studies.

[1] H. U. Keller *et al.*, Space Sci. Rev. **128**, 433 (2007).
[2] H. Sierks *et al.*, Science **334**, 487 (2011).
[3] J. B. Vincent *et al.*, PSS **103**, 57 (2014).
[4] R. V. Morris *et al.*, GCA **57**, 4597 (1993).
[5] `www.launchpad.net/esys-particle`
[6] H. Sierks *et al.*, Science **347**, aaa1044 (2015).
[7] N. Thomas *et al.*, Science **347**, aaa0440 (2015).

Poster 13 **Mathias Hummel**

Local Mach number determines the evolution of clustering in a free cooling granular gas

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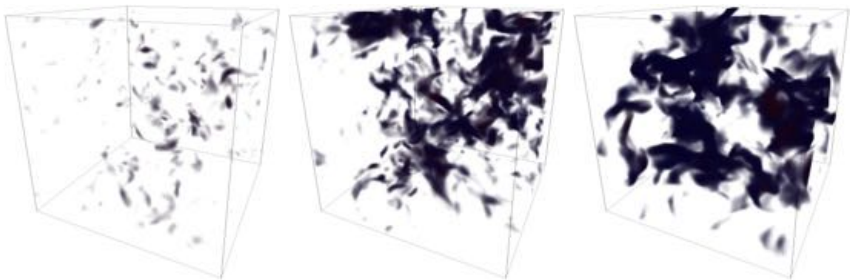
We perform direct numerical simulations (DNS) of granular hydrodynamics to study the clustering of a freely cooling granular gas for constant coefficients of restitution in three dimensions. Due to character of DNS we have the advantage of direct access to hydrodynamic quantities at each point in the simulated system. We find that the evolution of a granular gas is well described by the ratio between local bulk velocity and thermal velocity, that is the Mach number.

Figure 1 shows the temporal evolution of the density field of the granular gas. Figure 2(a) shows the temporal evolution of the fluctuations σ of the filling fraction for different ε values. different curves span many decades in time. Figure 2(b) shows the same data rescaled with the Mach number. The density evolution now nearly collapse on one master curve.



Snapshot of the 3D freely cooling granular gas, with effective coefficient of restitution ε=0.995 at times, from the left to the right, $t = 10^6$, $t = 10^7$ and $t = 10^8$. The dark regions show dense clustering, the light regions show the dilute gas, on a logarithmic scale.

[1] Nikolai V. Brilliantov, Thorsten Pöschel, *Kinetic Theory of Granular Gases* (Oxford University Press, 2004).

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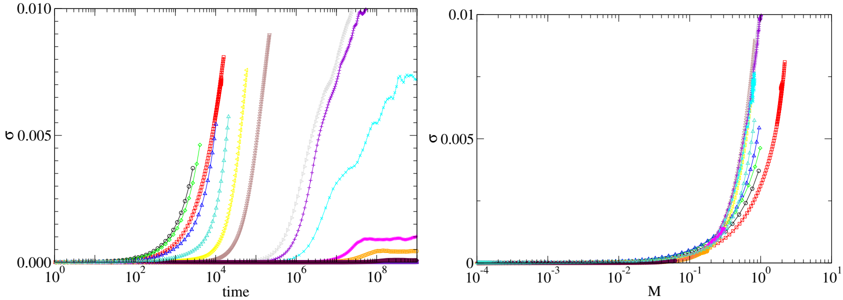

Dependency of the fluctuation of the filling fraction on time (left panel) and Mach number (right panel). The graph shows the values measured for effective coefficient of restitution $\varepsilon 0.01..0.99999$. The lines are guides to the eye.

[2] Miller, S. and Luding, S., *Cluster growth in two- and three-dimensional granular gases* (American Physical Society, 2004).

[3] Goldhirsch, I. and Zanetti, G., *Clustering instability in dissipative gases* (American Physical Society, 1993).

Poster 14 **Thorben Kelling**

Granular Matter as an Active Gas Pump in Reduced Gravitational Environments

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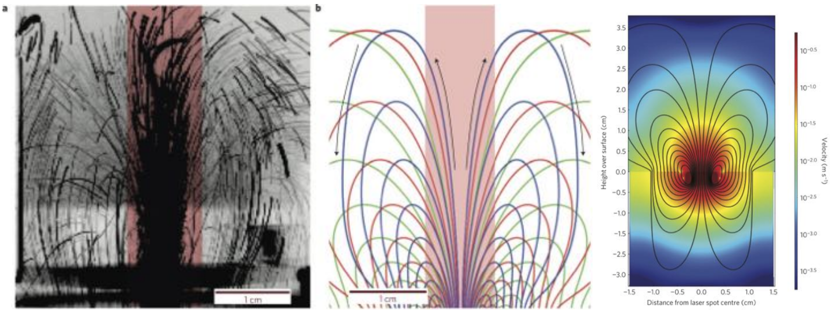
We just recently found in experiments that inhomogeneously heated granular matter create efficient gas flows in $10^{-1} - 10^{2}$ mbar environments [1, 2]. Temperature gradients over channels induce gas flows along the surface by thermal creep [3, 4]. In general the gas flows from the cooler towards the warmer side. In first experiments at the drop tower in Bremen (Fig. 63) we found that an illuminated basaltic dust sample induces gas motion up to cm/s, which is not only active above the dust surface but is also present centimeters below the surface.



Left: Superimposed images from the drop tower experiments showing particle trajectories following the gas flow. A laser (red bar, 8 mm diameter, 655 nm, 13 kW m^{-2}) illuminates a basaltic dust sample from above at 10 mbar ambient pressure. Particles are ejected within the illuminated spot. Due to the illumination and heating of the dust sample (see text) a gas flow is induced; **Center:** Model of the gas flow; **Right:** Simulation of particle velocities along their streamlines below and above the surface of the dust sample. The height 0 on the y-axis marks the surface of the dust bed [2].

The gas mass flow rates can be estimated by

$$\dot{M} = p_{avg} \sqrt{\frac{m\pi^2}{2k_B T_{avg}}} \frac{r^3}{l} \frac{\Delta T}{T_{avg}} Q_T,$$

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where p_{avg} and T_{avg} are the average ambient pressure and temperature, r is the radius and l the lenght of the channels within the dust sample, ΔT is the temperature difference between the channels ends, k_B is the Boltzmann constant, m is the molecular mass of the ambient gas and Q_T is a factor which depends on the Knudsen number $Kn = \lambda/(2r)$, which is the relation of the mean free path of the gas to the diameter of the channels here [2]. We found in the drop tower experiments a mass flow rate about $\dot{M} \simeq 10^{-14}$ kg s^{-1}. An induced gas flow within and above granular matter by thermal differences within the matter itself can have several impacts on different disciplines: The concept is applicable to the planet Mars ($\sim$ 0.38 g, mbar pressure), where the mechanism might act as a giant surface pump or might trigger the formation of dust devils and dust storms by supporting lifting forces. The thermal creep flows through dust aggregates can be used to levitate these aggregtes in the laboratory (artificial zero gravity) to study e.g. the collision behaviour of dust aggregates [1, 5] which is important for planet formation processes. In accretion disks around newly formed stars thermal creep might efficiently transport gas [6].

ACKNOWLEDGMENTS

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[1] T. Kelling and G. Wurm, PRL **103**, 215502 (2009).
[2] C. de Beule, G. Wurm, T. Kelling, M. Küpper, T. Jankowski and J. Teiser, Nature Physics **10**, 17-20 (2014).
[3] M. Knudsen, Ann. Phys. (Leipzig) **336**, 205 (1909).
[4] E. P. Muntz, Y. Sone, K. Aoki, S. Vargo, and M. Young, J. Vac. Sci. Technol. **A 20**, 214 (2002).
[5] T. Kelling, G. Wurm and M. Köster, APJ, **783:111**, 7pp (2014)
[6] T. Kelling and G. Wurm, APJL, **774:L1**, 2pp (2013)

Poster 15 **Vinita Kumari**

Equilibrium shapes of rotating self-gravitating asteroids

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This research looks at the dynamical behaviour of asteroids that are held together by the effect of self gravity. Granular aggregates are ubiquitous in nature which can display solid- or fluid-like behaviour. The behaviour of these aggregates depends on packing fraction, co-efficient of friction and particles properties. In particular, we employ DEM simulation to investigate equilibrium-shaped granular assembly [4]. The assembly is rotated by providing an initial angular velocity. This initial angular velocity is steadily increased until a critical value at which the aggregate fails. We explore the dependence of this critical angular velocity on the asteriod's shape of various particle parameters.

[1] P. Cundall and O. Strack, Geotechnique **29**, 47 (1979).
[2] Y. Tsuki, T. Tanaka and T. Ishida, Powder Technology **71**, 239 (1992).
[3] Zhang, W.J. Whiten, Powder Technology **88**, 59 (1996).
[4] D.P. Sanchez, D.J. Scheeres, Icarus **218**, 876 (2012).
[5] I. Sharma, J.T. Jenkins, J.A. Burns, Icarus **200**, 304 (2009).

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Poster 16 **Marc Köster**

Experimental Study On Bouncing Barriers In Protoplanetary Disks

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Dust aggregates interact in the early stage of planet formation in the protoplanetary disc through individual collisions. It has been observed in experiments that a bouncing barrier avoids growth in the regime of mm to cm sized dust aggregates [1]. In our work [2] we levitate simultaneously about 100 SiO_2 cylindrical, porous dust aggregates giving us free dust aggregates in the laboratory ('artificial zero-g') and observe their interaction in an ensemble (Fig. 63). The levitation itself is based on the Knudsen Compressor [3].
With velocities below mm/s up to cm/s more than 10^5 collisions occurred and nearly 2000 were analyzed in detail. To enhance the relative velocity between the aggregates a gas flow through a nozzle was used.
In spite of sticky collisions no stable net growth was visible in the aggregate ensemble. The total aggregate number remained constant over time (see Fig. 63). Secondary collisions on already attached aggregates disrupt their connection. Within the chosen parameter rage the experiment confirms the bouncing barrier as a limit of a self-consistent particle growth.

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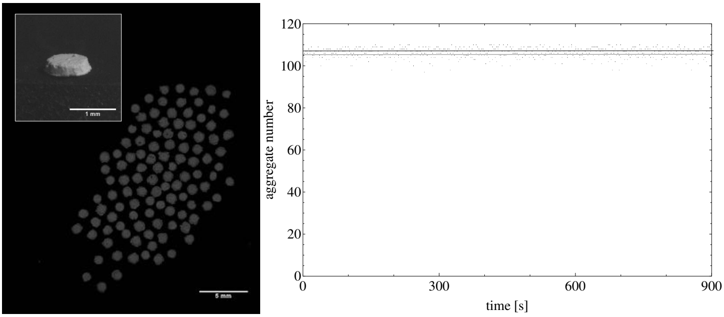

Left: SiO_2 aggregate sample, as observed by the high-speed camera. The inset is a microscope image of one of the aggregates. **Right:** Total number of aggregates during the recording phase (dark gray: no gas flow; light gray: nozzle gas flow activated). The solid lines are linear fits to the data.

ACKNOWLEDGMENTS

This work was funded by the University of Duisburg-Essen and by the Deutsche Forschungsgemeinschaft (DFG; project Ke 1897/1-1).

[1] A. Zsom, C. W. Ormel, C. Güttler, J. Blum, & C. P. Dullemond, A&A **513**, 56 (2010).
[2] T. Kelling, G. Wurm, & M. Köster, ApJ **783**, 111 (2014)
[3] M. Knudsen, AnPhy **336**, 633 (1909).

Poster 17 **Markus Küpper**

The Role of Insolation on Martian Aeolian Erosion

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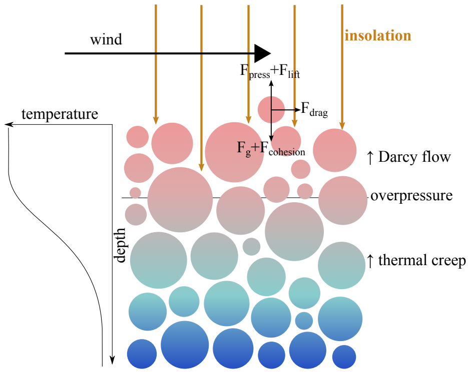
We present first results of our wind tunnel experiments on the effect of insolation on the aeolian erosion threshold. Temperature gradients in the dust bed induce thermal creep [5]. This leads to an overpressure just below the surface, which can be strong enough to eject the complete surface layer if enough illumination is provided [1]. It further leads to a gas flow through the dust bed [2]. As the illumination needed for ejection cannot be provided by insolation alone, we investigated the case when the illumination is lower and aids the aeolian erosion.



Schematic of the insolation assisted aeolian erosion

In the experiment it is observed whether grain detachment occurs. As sample material Mojave Mars Simulant [4] was used. Working gas was air at 6 mbar. By varying the airflow and the illumination the threshold of the erosion is measured. We rescale our findings to Martian conditions. In our experiment an reduction of about 10% for the Martian enviroment is found [3].

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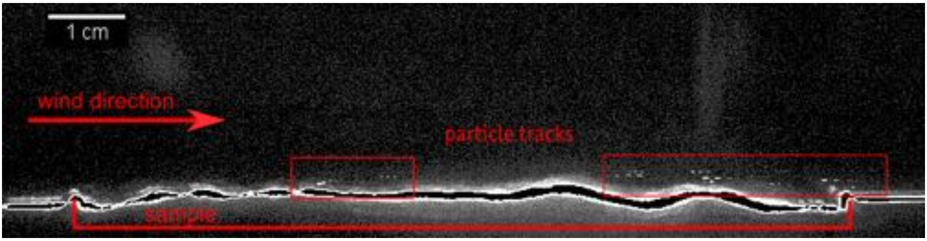

Example picture showing Erosion. This picture is an composite from a 2750 frames observation, processed to enhance the visibility of the particles. Observation was done with an pulsed line laser, leading to the striking triple exposed feature.

ACKNOWLEDGMENTS

This work was funded by the DFG.

[1] de Beule, C.,Wurm, G., Kelling, T., Koester, M., Kocifaj, M., 2015. *Lifting dust on mars: On the thickness of an insolation activated dust layer.* (submitted).

[2] de Beule, C.,Wurm, G., Kelling, T., Küpper, M., Jankowski, T., Teiser, J., 2014. *The martian soil as a planetary gas pump.* Nature Physics 10, 17-20.

[3] Küpper, M., Wurm, G. 2015. *Insolation assisted aeolian erosion on Mars: Wind Tunnel Experiments* (submitted).

[4] Peters, G. H., Abbey, W., Bearman, G. H., Mungas, G. S., Smith, J. A., Anderson, R. C., Douglas, S., Beegle, L. W., 2008. *Mojave Mars simulant - Characterization of a new geologic Mars analog.* Icarus 197, 470-479.

[5] Sone, Y., Itakura, E., 1990. *Analysis of poiseuille and thermal transpiration flows for arbitrary knudsen numbers by a modified knudsen number expansion method and their database.* J. Vac. Soc. Jpn. (33), 92.

Poster 18 **Marco Mazza**

A Maxwell Construction for Phase Separation in Vibrated Granular Matter

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Recent work has demonstrated that confined grains driven by a periodic external force can separate into a dilute phase and a dense phase via spinodal decomposition [1, 2], and exhibit behavior similar to the phase separation in a van der Waals gas [2–6]. In an equilibrium fluid the pressure at coexistence, P^*, as well as the binodal densities ϕ_g (gas) and ϕ_l (liquid) are determined by the requirements of mechanical and thermal equilibrium and by the minimization of the appropriate free energy. These constraints give rise to the Maxwell construction on the non-monotonic pressure-volume isotherm $P(v)$ [7]. This equal-areas construction uniquely identifies $P^* = P_{EA}$, the equal-areas pressure.

In a granular gas, clustering is observed whenever the restitution coeffitient $\varepsilon < 1$. If ε is close to unity (elastic limit), it is not surprising that the overall clustering behaviour can be described by concepts borrowed from equilibrium statistical physics [3–5, 8]. However, as the system is taken far away from equilibrium, its behaviour is expected to differ qualitatively from its equilibrium counterparts. In particular, a Maxwell construction, which directly derives from the minimization of a free energy functional, is not expected to hold. Surprisingly, we find (see Fig. 63) that an equal-areas rule (Maxwell construction) quite accurately predicts the coexisting binodal densities and the pressure for the liquid-gas phase separation to a few percent, even if the system is well remote from the elastic limit (with ε down to 0.65). We demonstrate that this results from the minimization of residual mechanical work associated with the fluctuations in the system.

[1] T.-Y. Wang and T. M. Hong, Phys. Rev. E **78**, 061301 (2008).
[2] J. P. D. Clewett, K. Roeller, R. M. Bowley, S. Herminghaus, and M. R. Swift, Phys. Rev. Lett. **109**, 228002 (2012).
[3] M. Argentina, M. G. Clerc, and R. Soto, Phys. Rev. Lett. **89**, 044301 (2002).

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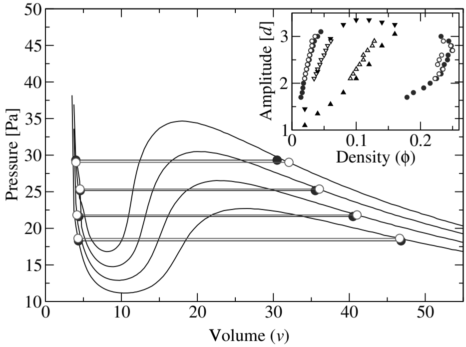

Main panel: The solid lines show the pressures calculated in small cells for driving amplitudes in the range $2.2d \leq A \leq 2.8d$. The filled circles show the corresponding binodal densities and the pressures calculated in long, thin systems. The open circles show the pressure and densities predicted using an equal-areas construction. Inset: Phase diagram for the liquid-gas-like phase separation. The filled and open circles show the binodal points determined by the long cell, and those predicted by $P(v)$ and the equal-areas construction, respectively. The triangles show the spinodal points from the long cell and those predicted by the unstable region of $P(v)$, respectively.

[4] R. Soto, M. Argentina, and M. Clerc, in *Granular Gas Dynamics*, Lecture Notes in Physics, Vol. 624, edited by T. Pöschel and N. Brilliantov (Springer Berlin Heidelberg, 2003) pp. 317–333.
[5] R. Liu, Y. Li, M. Hou, and B. Meerson, Phys. Rev. E **75**, 061304 (2007).
[6] K. Roeller, J. P. D. Clewett, R. M. Bowley, S. Herminghaus, and M. R. Swift, Phys. Rev. Lett. **107**, 048002 (2011).
[7] J. C. Maxwell, Nature **11**, 374 (1875).
[8] E. Khain, B. Meerson, and P. V. Sasorov, Phys. Rev. E **70**, 051310 (2004).

Poster 19 **Alexandre Meurisse**

Solar sintering of regolith

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Going back to the Moon to create a permanent outpost implies using the local resources. Consequently, regolith plays a key role for any In-Situ Resource Utilization (ISRU). One aspect of ISRU is extracting the oxygen from lunar regolith [1] but recent studies focused more on using the regolith as a construction material via, for instance, a sintering process [2], [3]. The sintering is a process of forming a solid mass by heat without reaching the point of liquefaction. This process, applied to regolith, could allow the building of bricks, walls for shielding and of roads and launchpads.

One issue working on such a process comes from a lack of true regolith (less than 400kg returned from Apollo missions). The scientific community is then obliged to use simulants, created from Earth basalt rocks. All main commercial simulants match around 99% the mare regolith mineral composition but they are all different which means that they likely behave differently at high temperature. The second issue is the sintering process. On the Moon, the regolith would be likely sintered focusing solar energy. Is the sintering by lunar radiation reproducible in a laboratory? Does vacuum change the process?

The main research question guiding this work concerns the investigation of several aspects of the sintering process for various regolith simulants. Three mare simulants are compared: JSC-1, JSC-1A and DNA. As shown in Fig. 1, even the two closest simulants (JSC-1A is a second batch of JSC-1) behave differently at the same temperature. Three sintering processes are also studied:

- Sintering in a solar oven.
- Sintering in a furnace in air atmosphere.
- Sintering in a furnace under vacuum.

[1] W. Seboldt, S. Lingner, S. Hoernes, W. Grimmeisen, R. Lekies, R. Herkelmann, D. Burt, *Lunar oxygen extraction using Fluorine*, J.S. Lewis, M.S. Matthews, M.L.

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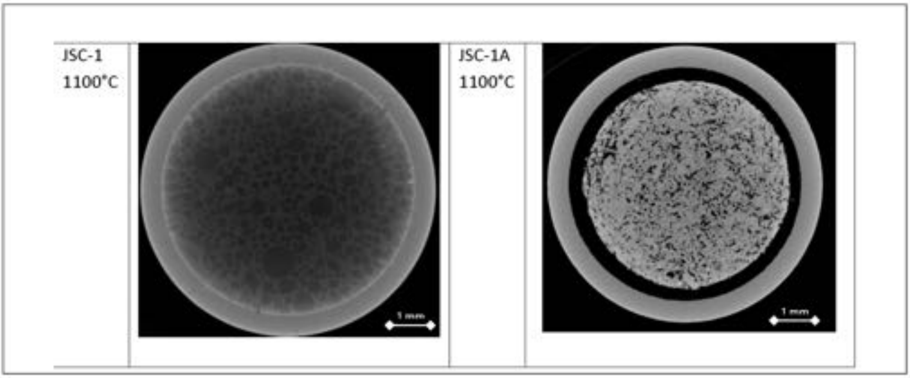

Tomogram of JSC-1 and JSC-1A simulants at 1100°C. JSC-1 is already melting while JSC-1A is only at the beginning of sintering.

Guerrieri (Eds.), Resources of Near Earth Space, U. Arizona Press, Tucson, AZ, 129-148 (1993).

[2] G. Cesaretti, E. Dini, X. De Kestelier, V. Colla, and L. Pambaguian, Acta Astronautica **93**, 430 (2014).

[3] E. J. Faierson, K. V. Logan, B. K. Stewart, M. P. Hunt, Acta Astronautica **67**, 38 (2010).

Poster 20 **Sebastian Mühlbauer**

Rarefied gas dynamics including chemical reactions

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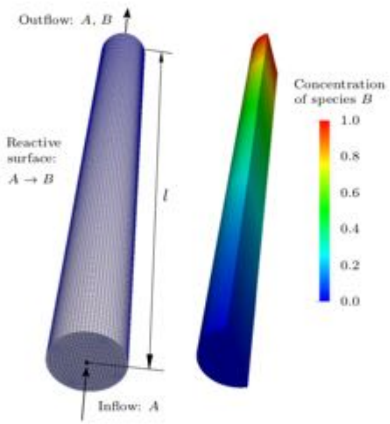
Rarefied gas flow is an important issue especially in regions of low gravity. Approaches employing continuum mechanics, however, are based on the assumption of local equilibrium, which is not valid for the density range of interest. Hence, particle based simulation methods have to be employed in this context. An invaluable advantage of such methods is that chemical models can be implemented on microscopic scale yielding results on macroscopic scale, which are independent from macroscopic reaction kinetics.



Left: Rarefied gas flow through a reactive pipe.

Right: Porous structure for further investigations.

Employing a particle based approach, we simulate chemical reactions on catalytic surfaces in rarefied gas flows. The starting point is non-dissociative adsorption with subsequent desorption as can for example be observed for carbon-monoxide on a platinum surface [1]. The underlying gas dynamics are simulated using Direct Simulation Monte Carlo [2], which allows for following the trajectory of each quasi-particle. If a reactive quasi-particle impinges on a reactive surface, it is adsorbed with a certain probability. Apart from constitutive parameters defined by the particle-wall-pairing, the adsorption probability depends on the

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local temperature. Naturally, low local surface coverage, which implies an abundance of free adsorption sites, encourages adsorption. Depending on the wall temperature the particles are desorbed again after a certain time and ready for another adsorption. For a confined container the numerical results are validated applying an analytical model.

Furthermore, we implement a qualitative surface reaction model by changing the particle behaviour after desorption preventing a second adsorption. The left part of the figure above depicts the particle concentration referring to species B in a rarefied pipe flow, where particles of species A are adsorbed and converted to species B on the lateral surface. This model allows for assessing different geometries – as displayed in the right part of the figure above – and flow conditions in terms of chemical surface reactivity.

[1] T. Engel and G. Ertl, Advances in Catalysis **28**, pp. 1–78 (1979).
[2] G. A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows* (Clarendon Press, 1994).

Poster 21 **Patric Müller**

Event-driven molecular dynamics of soft particles

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The dynamics of granular systems obeys Newton's equations of motion which are commonly solved numerically by (force-based) Molecular Dynamics (MD) schemes. Under low gravity conditions granular matter frequently assumes weakly bound states in which the rate of many-body collisions may be neglected compared to the rate of pair collisions. Further assuming instantaneous collisions the simulation of such systems can be accelerated considerably using event-driven Molecular Dynamics, where the coefficient of restitution is derived from the interaction force between particles. Recently it was shown that this approach may fail dramatically, that is, the obtained trajectories deviate significantly from the ones predicted by Newton's equations. We generalize the concept of the coefficient of restitution and derive a numerical scheme which, in the case of dilute systems and frictionless interaction, allows us to perform highly efficient event-driven Molecular Dynamics simulations even for non-instantaneous collisions. We show that the particle trajectories predicted by the new scheme agree perfectly with the corresponding (force-based) MD, except for a short transient period whose duration corresponds to the duration of the contact. Thus, the new algorithm solves Newton's equations of motion like force-based MD while preserving the advantages of event-driven simulations.

[1] P. Müller and T. Pöschel, Phys. Rev. E **87**, 033301 (2013).

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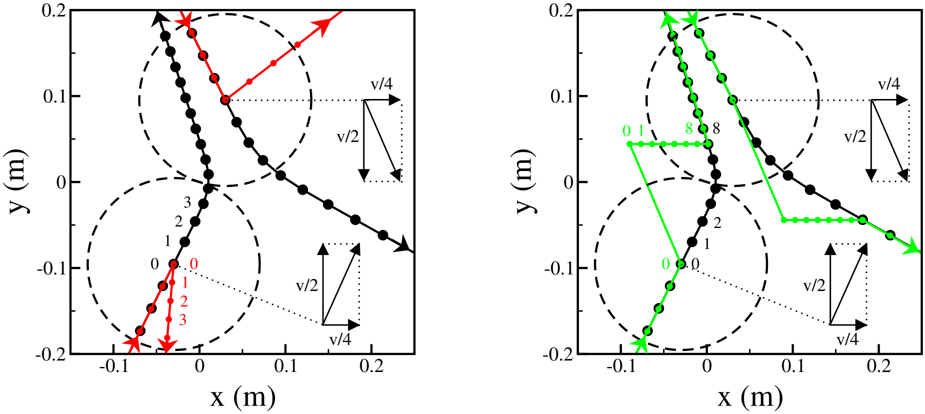

Traces of two colliding spheres. Black lines show the numerical integration of Newton's equation (MD), red lines (left) show the trajectories as obtained from event-driven MD with the assumption of instantaneous collisions. The green lines (right) show the trajectories as obtained by the suggested new algorithm. Symbols and numbers (of the respective color) indicate the particle positions at equidistant points in time. The number 0 stands for the moment when the particles touch and 7 corresponds to the end of the collision. The dashed circles show the spheres at the moment of impact.

Poster 22 **Loreto Oyarte Galvez**

Granular Rotor in the Non-Brownian Regime

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The attempts to challenge the second law of the thermodynamics have been many throughout history. In 1912, Marian Smoluchowski devised a prototype designed to convert Brownian motion into work, but 50 years later Feynman showed unambiguously why at thermal equilibrium this device cannot actually do this. However, far from equilibrium the behaviour of a rotor which rectifies motion of randomly moving molecules in their surroundings, is still an active matter of study.

We study experimentally and theoretically the movement of a granular motor, consisting of a horizontal rotor with four vanes immersed in a granular bath. The vanes in the rotor are precisely balanced around an axis, which in turn is connected to the container wall by a low-friction ball bearing, as showed in Fig.50-a. The angle is measured by an optical angle encoder.[1]

We studied the rotor in the single-kick regime. In this regime, the rotor is in rest for most of the time. Only occasionally a particle-vane collision sets the vanes into motion. Therefore the time between particle-rotor collisions is longer than the time the rotor needs to be stopped

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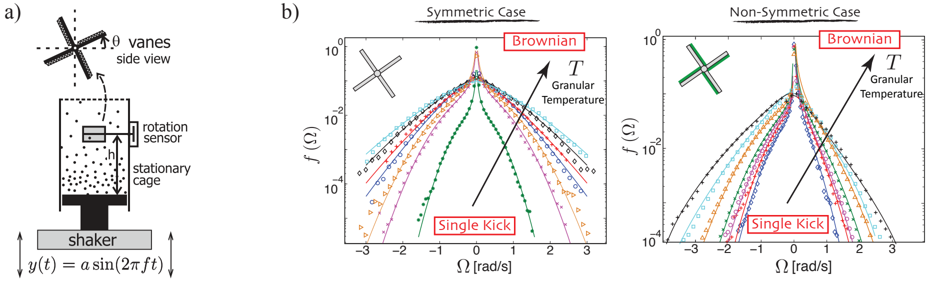

a) Schematic of the experimental setup. Side view of the vanes shows different material on each side implying a different coefficient restitution α_- (anti clockwise) and α_+ (clockwise). b) The AVD for increasing granular temperatures has been plotted, in the symmetric (left) and non-symmetric (right) cases. The symbols correspond to the experimental data (for $f = 20$, 22, 24, 26, 28, 30 and 32 Hz and $a = 1.4$ mm) whereas the lines represent the model.

We calculate the angular velocity distribution (AVD), which consists of a singularity corresponding to the time during which the motor is at rest, and a regular part corresponding to the relaxation after kicks [2]. From the experimental study, we observed a non-linear relaxation velocity, implying that the dynamic friction of the rotor is not constant in this regime. We used this observation in our model to obtain the regular part of the AVD.

With the goal of understanding the behaviour of the granular rotor, we injected more energy to the granular gas and, as a result, the time between particle-rotor collisions becomes comparable to the time the rotor needs to be stopped by friction ($\tau_c \sim \tau_s$). In this case, our model turns into in an integral equation which we solve using the corresponding eigenvalue problem.

The rotor can be symmetric or not. In the non-symmetric case, the rotor favours one of the two directions, which is known as the ratchet effect. We adapted our models to both regimes and compared with the experimental results, like in the symmetric cases.

Our models fit precisely to the experimental results in both regimes and for symmetric and non-symmetric conditions, as showed in Fig.50-b.

[1] P. Eshuis, K. van der Weele, D. Lohse, and D. van der Meer, Phys. Rev. Lett. **104**, 248001 (2010).
[2] J. Talbot, R. D. Wildman, and P. Viot, Phys. Rev. Lett. **107**, 138001 (2011)

Poster 23 **Felipe Pacheco**

The collapse of a gas cavity inside a granular material: craters and jets.

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Impact cratering has been revised intensively during the last decades using granular materials [1–3]. However, alternative processes that can also give rise to craters formation have been rarely considered. Here we study experimentally the cratering process due to the explosion and collapse of a pressurized air cavity inside a sand bed. The collapse generates a crater which dimensions and morphology are analysed in terms of the initial pressure, volume and shape of the cavity. Moreover, durign the last stages of the process, a collimated granular jet emerges from the collision of sand avalanches that converge concentrically at the center of the depression. We discuss the origin of theses jets in comparison with those observed in impact experiments [4, 5].

ACKNOWLEDGMENTS

This work was finantially supported by Conacyt-Mexico and VIEP-BUAP.

[1] A. M. Walsh, K. E. Holloway, P. Habdas, and J. R. de Bruyn, Phys. Rev. Lett. **91**, 104301 (2003).
[2] S. J. de Vet and J. R. de Bruyn, Granular Matter **112**, 6 (2011).
[3] F. Pacheco-Vazquez and J. C. Ruiz-Suárez, Phys. Rev. Lett. **107**, 218001 (2011).
[4] D. Lohse, R. Rauhe, R. Bergmann, adn D. van der Meer, Nature London **432**, 689 (2004).
[5] J. R. Royer, E. I. Corwin, A. Flior, M.-L. Cordero, M. L. Rivers, P. J. Eng, and H. M. Jaeger, Nat. Phys. **1**, 164 (2005).

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Poster 24 Joshua Poganski

Calibration of martian simulant soil for a dynamic penetration using a discrete element method

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Abstract
This paper presents a way to calibrate granular materials for the discrete element method (DEM) and shows the first results from a calibration of a martian simulant soil. For the calibration in the DEM it is necessary to get the material parameters of a single grain. The closer investigated calibration method is the triaxial compression test with preconsolidation and a drained specimen. The water content of the specimen is so low that it is not taken into account for the simulations. The simulations are done in LIGGGHTS, an open source discrete element method simulation software.

Introduction
The InSight mission of NASA in 2016 will explore Mars interior using a geophysical lander to investigate the interior and seismic activity of the planet. On board of the lander is the HP^3 instrument for measuring the heat flow and physical properties of the martian soil. This instrument places a set of thermal sensors up to five meters deep under the surface using a hammer mechanism implemented in the penetrator. To estimate the maximum reachable depth it is necessary to use numerical simulations. The simulation of a dynamical cone penetration test is associated with certain difficulties. These are the nonlinear behavior of the soil, the large deformations due to the penetration process and the high dynamics during the hammering. For that reason, the discrete element method is choosen to simulate the high dynamical process. The calibration of materials takes a large and important role in the numerical simulation. For the discrete element method it is necessary to determine the micro-scale material parameters of each particle. This is done by examining the macro-scale behavior that occurs due to certain micro-scale parameters and compare this to the real soil behavior [1]. The advantage of the discrete element method is that physical effects like dilatancy behavior and soil hardening are automatically captured by the particle geometries and the rearrangement of the particles. The calibration of the martian simulant soil is done by four experiments. These are an angle of repose experiment, particles on an inclined plane, an oedometer test and a

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triaxial compression test. The results of all calibration experiments are compared with the simulation results to determine the best parameter set for the DEM soil model. The change of the parameters and the comparison of the results are automatically done by an algortihm in an ad-on module to the LIGGGHTS software package. The non-spherical shape of real soil particles can be considered with a rolling friction model for the spherical particles in the simulation [2]. For this, a rolling friction torque that acts against the rotation of a particle is added to the particle. This torque corresponds to an eccentric normal contact force at the particle which originates from the non-spherical shape.

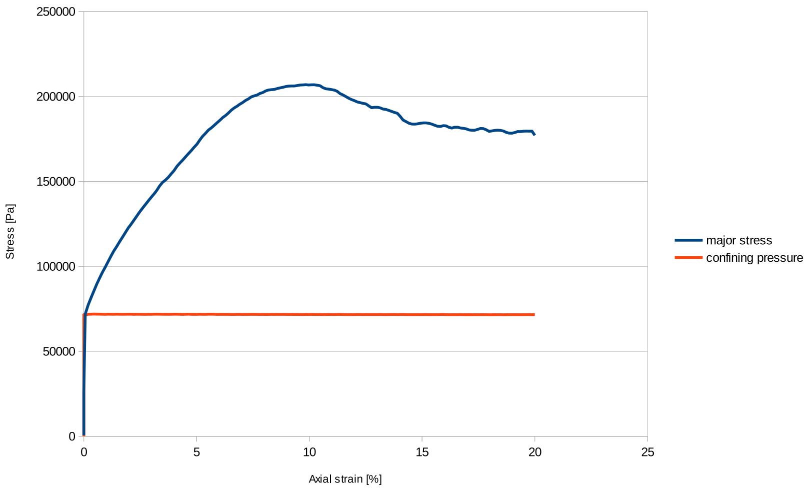
The triaxial compression test

The triaxial compression test in the laboratory is done in a cylindrical chamber with membrane walls and a confining pressure created by surrounding water. This is modeled in LIGGGHTS with a hexagonal prism chamber to approximate the cylindrical shape. This approximation is necessary to control the confining pressure in the DEM model. The side walls and the top wall are moved with a control unit, that regulates the force which acts on the walls. These walls move until a certain confining pressure is reached. If the confining pressure is reached, the bottom wall moves upwards with a constant velocity, while the force on the bottom wall and its position are computed. The deviatoric stress over axial strain diagram and the volumetric strain over axial strain diagram are used to compare the simulation with experimental tests. The main parameters for the simulation which has to be in good agreement with the real soil properties are the void ratio and the grain size distribution. To obtain a certain void ratio the micro-scale parameters are adapted until the structur is stable under gravity, whereas the grain size distribution can be set in LIGGGHTS.

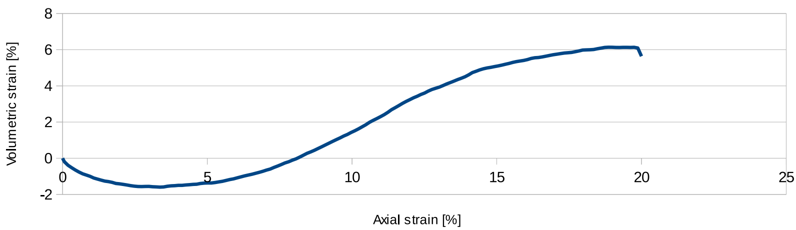
The results in figure 63 show the major stress computed at the bottom wall and the confining pressure computed at the side walls from a simulation in LIGGGHTS. There is a dilatant behavior of the soil, where the stiffness of the soil first increase and later decrease with further axial strain. It can also be seen that the confining pressure is well controlled by the control unit and remains constant. The volumetric strain over the axial strain is shown in figure 64, where one can obtain the change from compression of the specimen at the beginning to an increase of the specimen size with further axial strain. In both diagrams a critical state can be observed for large axial strain, where the deviatoric stress and the volumetric strain remains constant.

Conclusion

The triaxial compression test can be used to calibrate soil for a DEM simulation. In the observed case of a martian simulant soil the triaxial compression test is done under preconsolidated drained conditions. The results show that the physical behavior of a dry soil like a martian simulant soil can be well simulated with the discrete element method and that structural properties of soil like dilatancy, soil hardening and force chains are automatically captured with the discrete element method. The non-sphericity of real grains can be considered with a rolling friction model in LIGGGHTS. The calibration for the discrete element method can be done by examining the macro-scale soil behavior to derive the micro-scale soil parameters.



Triaxial compression test - stress over axial strain diagram



Triaxial compression test - volumetric strain over axial strain diagram

ACKNOWLEDGMENTS

[1] Cui L, O'Sullivan C, 2006, In: *GEOTECHNIQUE*, Vol: 56, Pages: 455-468, ISSN: 0016-8505

[2] Jun Ai, Jian-Fei Chen, J. Michael Rotter, Jin Y. Ooi, In: *Powder Technology*, Vol. 206, No. 3, 30.01.2011, p. 269-282.

[3] O'Sullivan, C. (2011). *Particle-Based Discrete Element Modeling: A Geomechanics Perspective.* (London: Spon Press/Taylor & Francis, 2011).

Poster 25 **Adeline Pons**

Sonofluidized granular packing under low gravity

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Under terrestrial gravity, introduction of weak acoustic vibrations induces rheological modification in a granular packing and glassy dynamics are observed [1, 2]. Here we study the effect of such vibrations on a granular packing under reduced gravity and micro-gravity. In absence of gravity the confining pressure can be fixed in principle at very low values without the limitation of hydrostatic pressure allowing us to reach unexplored confinement conditions.

The experiments were performed during different campaigns of parabolic Zero-G flights (provided by Novespace in Mérignac). We used two experimental set-ups. Both consist of a container filled with glass beads (bi-disperse, mean diameters 1 mm and 1.3 mm). For the first experimental set-up the packing fraction is imposed whereas the confining pressure is imposed for the second one thanks to a retroaction system acting on a piston at the top of the container (Figure 63a). In both case, the container presents a transparent window which permits to follow grains mobility by tracking the light reflection on each grains (Figure 63b). For any conditions we then characterize the state of the granular packing by its diffusivity coefficient D (Figure 63c).

The preliminary results of this study are the following. First, in both reduced and micro-gravity, dynamics observed are much faster than under terrestrial gravity. Secondly, we observed a mobility threshold in term of packing fraction induced by the acoustic vibrations. The value of this critical packing fraction ($\Phi \sim 0.64$) doesn't seem to depends on the value of the gravity. And finally, we also observed a mobility threshold in term of confining pressure ($40 - 50$ Pa) (Figure 63d). But unlike the case of packing fraction control, the transition doesn't seem to be induced by our acoustic vibrations as the vibrations of the plane itself are sufficient to induce fluidization (Figure 63d).

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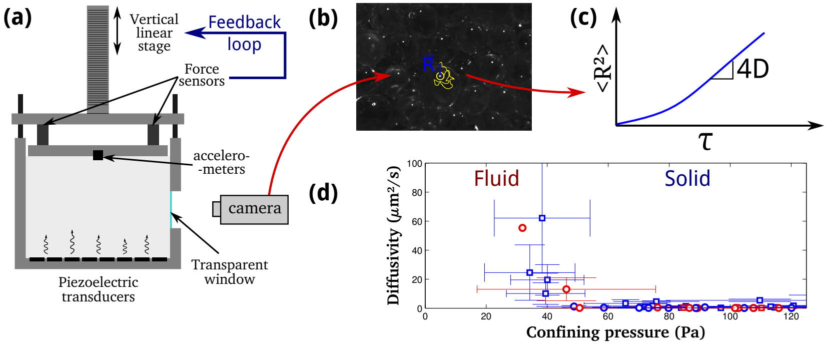

(a) schematic of the pressure controlled experimental set-up. (b) Crop of a typical image and grain displacement over one parabola. (c) Root mean square displacement of grains averaged over 25 to 50 grains. (d) Mobility transition in term of confining pressure with (blue) and without (red) acoustic vibrations.

ACKNOWLEDGMENTS

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[1] C. Caballero, E. Clément, Rheology of a sonofluidized granular packing Eur. Phys. E 30, 395 (2009).
[2] A.Caballero-Robledo, C.Goldenberg, E.Clément, Local dynamics and collective synchronization in a granular glass, Granular Matter, 14, 239-245 (2012).

Poster 26 **Christian Scholz**

Actively Rotating Granular Particles in Low Gravitational Fields

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The phase behavior of active matter, such as swimming bacteria, flocks of animals or even humans currently attracts significant attention in soft-matter physics. Naturally for living matter on earth gravity is relevant in some form. For example bacteria orient in external gravitation fields, to swim closer to the water surface, i.e. towards the sun. However conditions for life could be significantly different, in particular it is an open question whether low-gravity objects, such as asteroids can sustain primitive life forms.
Here we introduce a system of active granular particles. Such active granulates can be created using rapid prototyping technology using an ingenious walker design introduced in [1] (see Fig. 63(a)-(d)). These particles can be excited to perform active rotation, driven by external vertical vibrations, therefore called Vibrots. We apply a gravitational force perpendicular to the sense of rotation of the Vibrots and investigate the phase behavior of particle ensembles in dependence of the normal force acting on the system. The results are compared to recent numerical studies of actively rotating 2D particle mixtures [2].

[1] E. Altshuler, J. M. Pastor, A. Garcimartin, I. Zuriguel, and D. Maza, PloS one, **8**, 8, (2013)
[2] N. H. Nguyen, D. Klotsa, M. Engel, and S. C. Glotzer, Phys. Rev. Lett., **112**, 7, (2014)

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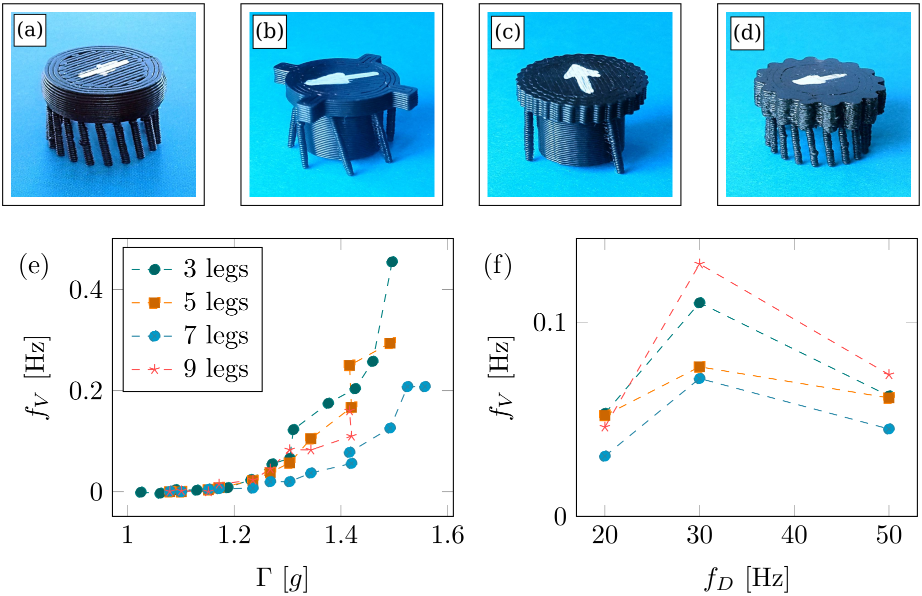

(a)-(d) Results of the rapid prototyping for different Vibrot shapes. (e) Dependence of the rotational frequency of the Vibrot f_V on the driving acceleration Γ for Vibrots with a different number of legs. (f) Dependence of f_V on the driving frequency f_D at $\Gamma = 1.33$ for different number of legs.

Poster 27 **Rainer Schräpler**

The Stratification of Regolith on Celestial Objects

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All atmosphere-less planetary bodies are covered with a dust layer, the so-called regolith, which determines the optical, mechanical and thermal properties of their surface. These properties depend on the regolith material, the size distribution of particles it consists of, and the porosity to which these particles are packed. We performed experiments in parabolic flights to determine the gravity dependency of the packing density of regolith for solid-particle sizes of 60 μm and 1 mm as well as for 100-250 μm-sized agglomerates of 1.5 μm-sized solid grains. We utilized g-levels between 0.7 m s^{-2} and 18 m s^{-2} and completed our measurements with experiments under normal gravity conditions. Based on our experimental data as well as on previous experimental and theoretical literature data, we developed an analytical model to calculate the regolith stratification of celestial rocky and icy bodies and estimated the mechanical yields of the regolith under the weight of an astronaut and a spacecraft resting on these objects.

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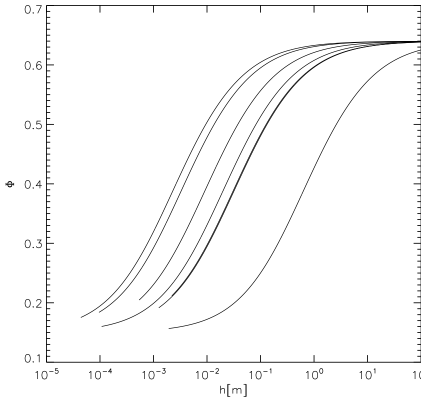

The packing density as a function of depth of the regolith (with particle diameters given in parentheses) of (from top to bottom) Mercury (44 μm), the Moon (96 μm), Dodona (0.6 mm), Vesta (108 μm), Phobos (2.2 mm), Steins (1.3 mm), 1996FG3 (2.0 mm), respectively.

ACKNOWLEDGMENTS

This research was supported by the Deutsches Zentrum für Luft- und Raumfahrt under grant no. 50WM1236. We thank TU München and the European Space Agency for providing the parabolic flights, Novespace for yet another professional and flawless campaign onboard their parabolic aircraft, and Eike Beitz for the SEM microscopy of our 1.5μm samples.

Poster 28 **Mathias Schywek**

Mars Regolith as a Natural Low Pressure Gas-Pump Studied in a μg-Experiment

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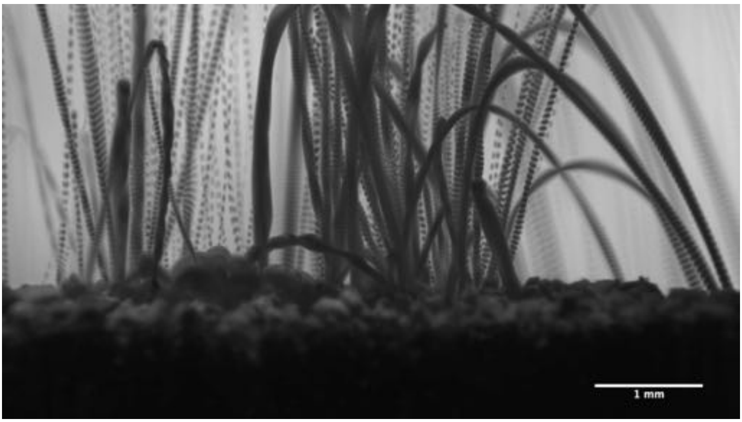
Project MAREG is a follow-up project of EULE (DLR 50 WM 1242) that focused on outbursts and ejections of dust particles induced by radiation and the corresponding temperature gradient in a dust sample [1–3]. Micro-gravity experiments showed an unexpected and exceptionally strong gas flow near the dust surface. The goal of MAREG is to clarify the conditions and strength of this gas flow and its dependency on micro-porous structure, layer thickness, gas pressure and temperature gradient. To avoid thermal convection micro-gravity is mandatory. The project will therefore utilize droptower experiments and parabolic flights.



Particles tracing gas flow under gravity

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ACKNOWLEDGMENTS

This project is supported by DLR Space Management with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant number DLR 50 WM 1542.

[1] de Beule, C., Wurm, G., Kelling, T., Kuepper, M., Jankowski, T., Teiser, J. 2014, Nature Physics, 10, 17-20
[2] de Beule, C., Wurm, G., Kelling, T., Koester, M., Kocifaj, M. 2015, submitted to Icarus
[3] de Beule, C., Kelling, T., Wurm, G., Teiser, J., & Jankowski, T. 2013, ApJ, 763, 11

Poster 29 **Abhinendra Singh**

Granular flow behavior in Extraterrestrial space

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Gravity is a critical factor in many natural (granular) phenomena like avalanches, landslides, sand-piles and even in some industrial applications [1]. Gravity-driven flows have also been observed on other planetary bodies of our Solar System and are of particular importance in understanding the geology of other planets and asteroids as well as for the human exploration of the Moon and Mars in the coming decades [2]. Despite its importance, the effect of gravity on granular flows is still poorly understood.

We study the steady shear rheology of granular materials in slow quasi-static states and inertial flows. Series of Discrete Element Method simulations are performed on a weakly frictional granular assembly in a split-bottom geometry considering various gravity fields. While traditionally the inertial number I, i.e., the ratio of stress to strain-rate timescales describes the flow rheology [4], we find that a second dimensionless number, the ratio of softness and stress timescales, must also be included to characterize the bulk flow behavior [1]. For slow, quasi-static flows, the density increases while the effective (macroscopic) friction decreases *non-trivially* with increase in gravity. This trend is added to the $\mu(I)$ rheology and can be traced back to the anisotropy in the contact network, displaying a linear correlation between effective friction and deviatoric fabric in the steady state. At low gravity, the system also shows various other interesting features like convective instabilities. A detailed analysis of granular shear flow behavior in low gravity and how that affects a related phenomena such as segregation will be presented.

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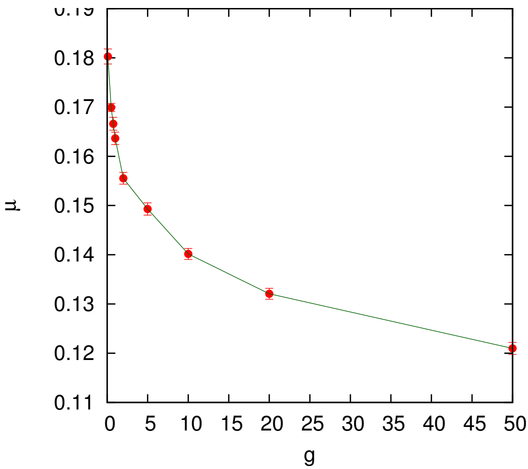

Effective friction coefficient $\mu = \frac{\tau}{p}$ plotted against gravity level (in ms^{-2}).

ACKNOWLEDGMENTS

This work was financially supported by the NWO-STW VICI grant 10828.

[1] Jaeger, H. M. and Nagel, S. R. and Behringer, R. P., Rev. Mod. Phys. **68**, 1259 (1996).
[2] K. J. Krohn *et al.*, Icarus **244**, 120 (2014).
[3] A. Singh, V. Magnanimo, K. Saitoh, and S. Luding, arXiv **1412.0874** (2014).
[4] P. Jop and Y. Forterre and O. Pouliquen, Nature, **441**, 727 (2006).

Poster 30 **Severin Strobl**

Dilute gas flows in complex geometries

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Dilute gases contained in porous materials in low gravity environments can lead to the interesting effect of dust ejections from the surface of planetary bodies in the presence of temperature gradients [2]. Due to a pressure build-up below the surface of dust layers following from a temperature gradient within the material, single particles can be ejected from the surface if the local pressure forces overcome the tensile strength. As the mean free path of the dilute gas is on the same length scale as the particle size, channels formed between the grains of the porous material act as a Knudsen compressor [3], leading to the pressure increase in regions with higher temperature. Experimental measurements of the local temperature and pressure fields can not be performed directly, which necessitates numerical simulations of the system.

Aside from the challenges posed by the complex geometries of porous materials, the low density of the gas flow leads to an additional difficulty: The velocity distribution in boundary regions is non-Maxwellian, an effect which becomes more and more pronounced at decreasing densities or smaller scales, respectively. While for dense fluids the boundary layer is very thin in comparison to the whole domain, for dilute gases with a locally high Knudsen number the effect is not negligible. Here the continuum assumptions of the Navier-Stokes equations may be violated and velocity slip at the gas-solid boundaries has to be taken into account. The gas phase is hence modeled using the direct simulation Monte Carlo (DSMC, [1]) method, which inherently includes non-equilibrium effects. For the simulation of the solid material, different approaches are used. A very efficient description of the porous media can be achieved by representing the particles as exact geometric objects and using the idea of constructive solid geometry (CSG) to combine those (Fig. 58).

If in addition to the gas phase also the temperature field in the solid material should be taken into account, a coupled fluid-solid simulation can be used. Here the gas phase is modeled using DSMC again, but additionally the heat equation is solved numerically inside of the solid using a finite element method (FEM). A full two-way coupling between the solid and the gas phase is performed, di-

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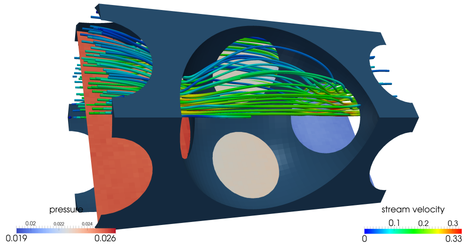
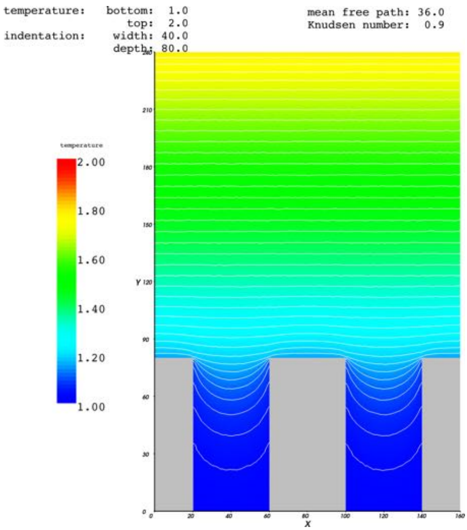


Streamlines and pressure field of a gas flow through a porous material created by a sphere packing.

rectly modeling the interaction between the two phases via a common interface (Fig. 59). The simulation is performed by alternating between the DSMC and FEM simulation and coupling both via a continuous adjustment of the boundary conditions.



Simulation of the temperature field of a dilute gas contained in the micro-channel formed by a hot (top) and cold (bottom) wall featuring two indentations in the lower region.

[1] G. A. Bird: *Molecular Gas Dynamics and the Direct Simulation of Gas Flows* (Oxford Science Publications, 1994).
[2] T. Kelling, G. Wurm, M. Kocifaj, J. Klačka, and D. Reiss, Icarus **212**, 935 (2011)
[3] M. Knudsen, Ann. Phys. **336**, 1 (1909)

Poster 31 Gonzalo Tancredi

Laboratory experiments to simulate the formation of dust comae and size segregation on asteroids

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Some observations of minor bodies of the Solar System have shown that granular material is present on the surfaces and maybe in the interior of these bodies. For example, m-size boulders have been observed on the surface of Itokawa as well as sand grains. Dust clouds formed after an impact has been detected in several main-belt asteroids.

Results related to the physics of Granular Media can be used to understand the physical evolution of these objects. We present some laboratory experiments devoted to study some processes relevant to these problems.

''Main-belt comets' or activated asteroids and the 'Cocoa Effect'

A few objects in typical asteroidal orbits have shown some kind of activity-like appearance due to the presence of a dust comae. They have been named as "Main-belt cometsör activated asteroids [1]. It is still uncertain whether the dust activity is triggered by the sublimation of ices or by some other process. Several explanations to the phenomena have been postulated. We have presented an alternative model based on the hypothesis that the coma is produced by dust particles being lifted by the seismic shaking produced after an impact.

The device used in the experimental setup is a box partially filled with different types of dust: talc, fine sand and thick sand and then dropped (free fall) from $\sim 40\ cm$, impacting the floor at a speed of $\sim 2.5\ m/s$. The box is connected to a vacuum pump to better simulate the conditions on an asteroid's surface. The purpose of these experiments is to simulate a quake coming from below. This quake could be produced by a distant impact and the transmission of a shock through the entire object.

When working with talc a big dust cloud is clearly seen after the fall (Fig. 60). In case of fine sand , a much smaller sand cloud can still be noticed. Apparently, no cloud is formed when working with thick sand.

We have called this phenomena the "cocoa effect", because it can be easily observed when a can of cocoa or any fine powder falls and knock the floor.

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Sequence of photos of the production of a cloud of talc.

Itokawa and the 'Brazil Nut Effect'

The distribution of boulders on the surface of Itokawa is correlated with the surface gravity. Large boulders are in the regions of high gravitational potential, while small-boulders are in the region of low gravitational potential. A size segregation or Brazil nut effects has been proposed to explain such correlation.

Consider a recipient with several large ball on the bottom and a larger number of smaller ones on top of it. All the balls have similar densities. After shaking the recipient for a while, the larger ball rise to the top and the small ones sink to the bottom ([2]). This is the shaking induced size segregation or Brazil nut effect (BNE) .

Most of the experiments in the literature have considered spherical particles under the influence of a sinusoidal shaking process. We would like to investigate the effects of irregular shapes under a impact shaking process. We have used the same experimental device described above: the falling box. We fill the box with a mixture of cm-size boulders, sand and/or talc. And we repeatedly lift and release the box, simulating a sequence of quakes coming from below.

Depending on the compaction of the fine powder, the BNE is observed or not. For fine talc, we do not observed the effect, but it is observed for coarse sand and boulders.

[1] Hsieh, H., Jewitt, D.: A Population of Comets in the Main Asteroid Belt, Science, 312, 561-563, 2006.

[2] Rosato, A., Strandburg, K., Prinz, F., Swendsen, R.: Why the Brazil nuts are on top: Size segregation of particulate matter by shaking, Physical Review Letters, 58, 1038 - 1040, 1987.

Poster 32 **Deepak Tunuguntla**

Effects of low and hyper gravity on particle segregation in bidisperse mixtures subject to low and hyper gravity

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Motivated by the work of Singh *et al.* [1], we focus on studying the effects of varying magnitude of gravity on dense bidisperse mixtures flowing rapidly over inclined channels. To investigate their effects, we apply discrete particle simulations (DPMs) as setup in Tunuguntla *et al.* [3], see Fig. 61.

As usual, the flowing bidisperse mixtures varying in size segregate eventually, i.e., large particles rise up towards the free-surface and smaller particles settle near the base. We use the approach of Thornton *et al.* [2] and compute the segregation Peclet number, P_s, for different magnitudes of gravity. P_s is the ratio of segregation velocity to diffusion rate, $P_s = S_r/D_r$. As a result, the Peclet number is found to decrease with the increasing magnitude of gravity. On the other hand, by tracking the vertical center of mass of both large and small particles, we determine that the segregation velocity is proportional to $\sqrt{g}$, which is consistent with several continuum formulations. However, in contradiction to slowly sheared flows reported in Singh *et al.* [1], the above stated observations imply that the rapidly sheared flows tend to diffuse more as the magnitude of gravity increases.

[1] Singh, A., Magnanimo, V., Saitoh, K. & Luding, S. 2014 Role of gravity or confining pressure and contact stiffness in granular rheology. *arXiv preprint arXiv:1412.0874* .

[2] Thornton, A. R., Weinhart, T., Luding, S. & Bokhove, O. 2012 Modeling of particle size segregation: Calibration using the discrete particle method. *Int. J. Mod. Phys.* **23**.

[3] Tunuguntla, D. R., Bokhove, O. & Thornton, A. R. 2014 A mixture theory for size and density segregation in free-surface shallow granular flows. *J. Fluid Mech.* **749**, 99–112.

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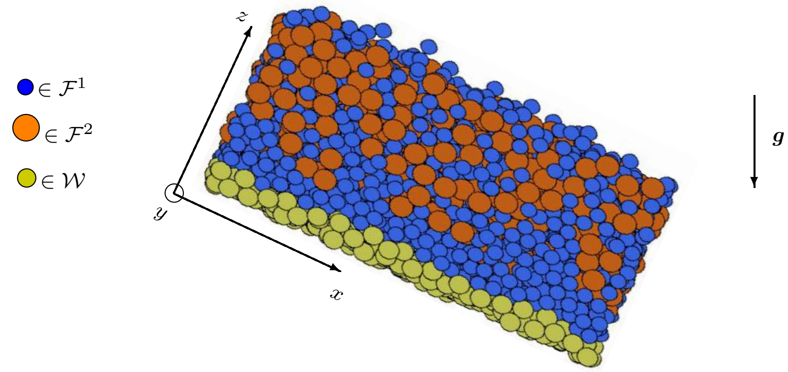

A snapshot of bi-disperse mixture flowing in a periodic box inclined at 26° to the horizontal (discrete particle simulation). Colours/shades indicate the base (yellowish green, $\mathcal{W}$), species type-1 and type-2 (blue, $\mathcal{F}^1$ and red, $\mathcal{F}^2$).

Poster 33 **Andrei Vedernikov**

Development of the equipment for forced clustering in microgravity experiments on dust clouds

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Thermophoresis, photophoresis and thermal creep are used in the equipment development and investigation of dust particle interaction, kinetics of clustering, formation of extended extremely fluffy clusters and of their detailed microstructure within the European Space Agency's scientific program Interactions in Cosmic and Atmospheric Particle Systems (ICAPS) [1]. For proper experimental conditions, the cloud should be prevented from sweeping away by residual external forces, mostly thermophoretic; from cloud dispersion due to Brownian motion; and from slowing down of aggregation rate due to particle number decrease and particle size growth. We developed a cloud manipulation system [2] that counterbalances external perturbations, provides cloud trapping and dust particle number concentrating (cloud squeezing). The equipment allows handling dust clouds initially containing millions of micron-sized particles per cubic centimeter with the total cloud volume of about several tens of cubic centimeters, pressure in the range 10–1000 Pa, room temperatures, total chamber volume of about 0.3–1 liter. Thermophoresis appeared to be most favourable for cloud manipulation. Thermal gradient creates arbitrary oriented and time dependent force by the help of a set of thermoelectric modules. Thermophoretic particle velocity at our experimental conditions does not depend on particle sizes, being great advantage for the investigation of clustering. Contrary to the electrostatic force, it does not create artificial particle-particle interaction in the cloud. A single cluster may thus be grown out of the whole cloud. The cloud manipulation system additionally provides temperature stabilization or, on the contrary, high temperature variation in the observation volume; formation of controlled temperature gradients, intensive three-dimensional periodic shear flow or three-dimensional gas density pulsations of the contraction-expansion type; application of electrostatic gradients including electrodynamic balancing; etc. Their choice and/or

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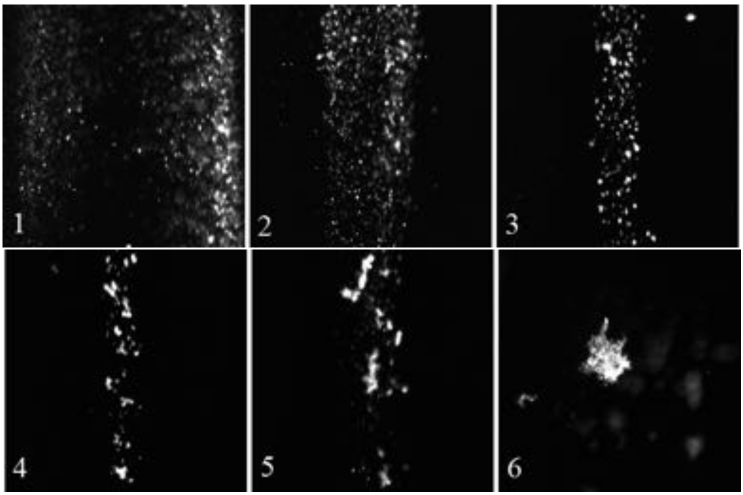
combination depend upon particular experimental task. The tests in short duration microgravity conditions of the Bremen drop tower [3] allowed us observing controlled cloud displacement, trapping, formation of complex three-dimensional cloud patterns and rapid growth of extended agglomerates as illustrated on the set of images below. Within the period of less than 5 seconds, the equipment allowed to grow clusters of up to 1 mm from clouds initially composed of 1.5 μm sized spherical particles under 30 Pa.

For the investigation of granular matter at low gravity conditions, the main advantage of the developed cloud manipulation system resides in providing opportunities for forced clustering — applying forces depending on the differences in cluster properties, creating shear gas flows, injection of test particles into the cloud.



Cluster growth in the thermophoretic trap: 0.5 ms between images, image size 4x4 mm.

ACKNOWLEDGMENTS

ESA PRODEX program, the Belgian Federal Science Policy Office, and ZARM Drop Tower Operation and Service Company Ltd. are greatly acknowledged.

[1] J. Blum, et al. Europhysics News **39**, 3 (2008).
[2] A. Vedernikov, et al., in: *Proceedings of the International Astronautical Congress* (IAC, 2012), pp. 777–787.
[3] E. Kufner, et al. Microgravity Science and Technology **23**, 4 (2011).

Poster 34 **Zhigang Zhou**

Sound propagation in Triaxial Sheared Glass Beads

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Ultrasound wave propagation in triaxial stressed glass beads is studied. A GCTS triaxial tester (see Fig. 1) is used. The triaxial equipment is affiliated with a pair of ultrasonic platen to measure the sound velocity in glass bead sample. The sample is confined in different boundary conditions under external pressures. The size of the glass beads are within 0.1mm to 1mm. The diameter and height of the sample are respectively 50.0mm and 65.5mm. Three experiments are done(see figure2): 1. the sample is pressed isotropically in axial and radial direction; 2. The confining pressure is kept constant, and the sample is pressed in axial direction; 3. The sample is placed in a cell of rigid wall and pressed in axial direction, i.e. uniaxial compression.

The sound velocity in isotropic and uniaxial boundary conditions changes with axial pressure to the power 1/6, predicted by Effective Medium Theory; however, in the boundary condition of the constant confining pressure, axial load dependence deviates from 1/6, especially when the sample strain increases. Furthermore, experimental measurement also found that the pressure dependence of sound velocity changes with the particle size distribution.

Triaxial tester(left) and ultrasonic platens(right).

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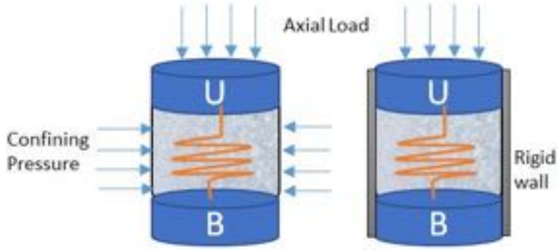
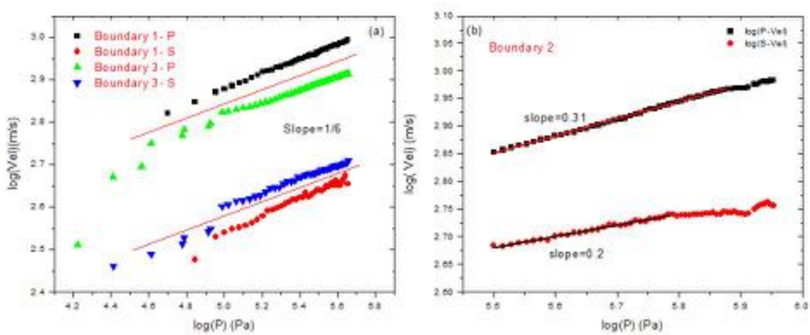


The sample models in different boundary conditions. Condition 1: Isotropic boundary, the glass beads are packaged in granular column using thin rubber membrane and kept the axial load same as the confining Pressure. Condition 2: Confining pressure is kept as 300kPa with changing axial load; Condition 3: the glass beads contained in a rigid cylinder container are pressed in axial direction.



(a) and (b) are the sound velocity results of different boundaries. The velocity in boundary 1 and 3 increases with pressure to the power 1/6; the velocity in boundary 2 deviates from 1/6, and changes its slope when radial strain becomes larger.

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