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The stratification of regolith on celestial objects

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ABSTRACT

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 the 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 previous experimental and theoretical literature and supported by our new experiments, 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.

1. Introduction

Gary et al. (1972) state that "Regolith is a mantle of loose incoherent rocky material of various origins that forms the surface of planetary bodies". Its size distribution determines the optical, mechanical and thermal properties of these surfaces. On bodies without atmosphere, regolith is formed by high-velocity impacts of interplanetary particles of different sizes. These impacts produce ejecta material with a size and velocity distribution determined by the impactor and target properties. Ejecta with velocities lower than the escape velocity of the target body are reaccreted and, thus, form the regolith on the surface. Laboratory experiments of Hartmann (1985) found ejecta velocities depending on the velocity of the impactor. The experiments of (e.g. Fujiwara and Tsukamoto, 1980; Nakamura et al., 1994) and studies of crater structures on the Moon (Vickery, 1986, 1987) showed that smaller particles are ejected at higher velocities than the larger ejecta. Finally Bottke et al. (2002) calculated in their chapter III the trajectories and re-accretion of ejected material on small celestial objects depending on its velocity. Therefore, the regolith size distribution should depend on the escape speed and, hence, on the size of the target body. Gundlach and Blum (2013) developed a method to correlate the size of the regolith particles with the thermal conductivity of the regolith. Thus, from measurements of the thermal inertia of small objects in the Solar System, their regolith-particle size can be estimated. The regolith filling factor, i.e. the packing density of the regolith particles (or 1 − porosity), enters their calculation as a free parameter. Gundlach and Blum (2013) found that objects with a size smaller than 100 km are covered with regolith particles of the size of ∼1–10 mm, whereas larger objects carry regolith with particle sizes of 10–100 μm.

Skorov and Blum (2012) model comet nuclei as consisting of macroscopic dust and ice agglomerates. In a recent work, Blum et al. (2014) showed that this model can explain the observed continuous activity of comets in the inner Solar System. Inside the comet nucleus, the dust and ice agglomerates are only subjected to the weak gravitational force of the comet, which leads to a stratification of the packing density within a comet nucleus. On celestial objects the regolith is compacted by their gravitational force, which leads to a stratification where the filling factor of the regolith increases with layer depth.

However, the texture (e.g. particle size distribution and packing density) and vertical stratification of regolith is basically unknown for all celestial objects except for the Moon (Heiken et al., 1991). Recently, Kiuchi and Nakamura (2014) related the particle size to the porosity for a variety of celestial objects. However, they used a simplified model in their analysis that implies that the packing density depends only on the ratio of the gravitational force of the contact force of a regolith particle. A result of this simplification is that the packing density of the regolith does not change with depth. If this was true, it would be impossible to compress loosely packed regolith at all. Thus, the results of Kiuchi and Nakamura (2014) are valid for the uppermost layer of the regolith where hydrostatic compression is small.

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We will show in this article that stratification of regolith due to hydrostatic compression is important and can be calculated with the relation between pressure and filling factor of the regolith found in our article. With this information, also the yield of objects on the surface of the regolith-covered celestial objects was derived.

For μm sized grains, this relation is experimentally obtained (see Section 2 by compressing the regolith with a piston in a cylinder as shown by Güttler et al., 2009). For the 10 μm grains, we measured the low-pressure part of the compression curve by adding thin layers on a regolith to compress it by its own weight and the high pressure part by compressing the regolith by a piston. For grains larger than 50 μm, the regolith is compacted to RCP (random close packing, its highest possible filling factor) by its own gravitational force for thicknesses above a few particle layers. We therefore did most of these measurements in the low-gravity environment aboard the Zero-G-plane of the European Space Agency. However, in spite of that, it was only possible to measure the upper 20% of the compression curve (see Section 2.3). It was therefore necessary to develop a model for the full compression curve (see Section 3) in which only one parameter must be experimentally determined. With this analytical model, we could additionally reproduce the relation between filling factor and grain radius found by Yang et al. (2000) at constant *g* and can show the consistency of our model (see Section 3).

To simulate the stratification of the packing density within a comet nucleus, we additionally used in our experiments 0.1–0.25 mm-sized dust agglomerates consisting of 1.5 μm-sized mono-disperse and spherical SiO_2 grains. We performed our measurements with mono-disperse spherical monomer particles to ease the theoretical approach to our measurements, whereas the particles on celestial objects will most likely be irregular and polydisperse. However, our previous measurements in Blum et al. (2006) showed that the results will not change dramatically for these particles (see Section 4).

In Section 2, we describe our experimental approach and the experimental findings. Section 3 uses the analytical-approximation form of Güttler et al. (2009) and the results of Dominik and Tielens (1995) and Krijt et al. (2014) to model the observed regolith stratification. In Section 4, we derive filling-factor profiles of the regolith for selected small rocky and icy bodies and estimate the mechanical yield of the regolith under the weight of an astronaut and a spacecraft, resting on these objects. Finally, Section 5 summarizes our results.

2. Experimental approach

In this Section, we describe the experimental methods developed and applied for the determination of the pressure-dependent filling factor of regolith and the results we received in parabolic-flight and laboratory experiments.

2.1. Particle samples

As regolith analogs, we used amorphous SiO_2 spheres with diameter of 10 μm, glass spheres with 60 μm diameter from unknown glass type, spherical soda lime particles with 1 mm diameter, and agglomerates of 1.5 μm-sized amorphous SiO_2 spheres with 100–250 μm diameter. Fig. 1 shows the size distributions and microscopic images of these samples. The experiments were performed at 10^5 Pa ambient pressure. Laboratory, microgravity and hypergravity experiments were performed with all samples with the exception of the 10 μm-sized particles. These particles fluidized under microgravity conditions, due to the ambient gas pressure, and could, thus, not deliver reliable results. For these particles, we only analyzed the experiments conducted in the laboratory. The humidity of the air inside the experiment could increase the contact forces of the particles and therefore decrease their filling factor at a given pressure. To find this influence we did ground experiments for the 10 μm-sized particles at 10 Pa gas pressure and at ambient (10^5 Pa) air pressure (asterisks and triangles in Fig. 4) and found no deviation within our error bars.

2.2. Experimental setup

2.2.1. Parabolic-flight experiments

Parabolic-flight experiments under reduced and hyper-gravity conditions were performed onboard the ZERO-G Airbus A300 aircraft. Typically, several experimental setups are mounted in the passenger area of the aircraft and are operated by onboard experimentalists during the flights. In one such flight, the aircraft performs up to 31 parabolic and catenary-curve flight maneuvers.

During a parabolic flight maneuver, inertia forces completely cancel Earth's gravity and the aircraft and all experiments onboard are completely weightless. During a catenary-curve flight maneuver, inertia forces partly cancel Earth's gravity and the aircraft and all experiments are partly weightless so that the environment of celestial bodies with surface accelerations smaller than on Earth can be simulated.

In the flights described here, the flight maneuvers consisted of 13 catenary curves with martian ($0.38g$), 12 with lunar ($0.17g$) and 6 parabolas at zero gravity, respectively. Here $g = 9.81\ \mathrm{m\ s^{-2}}$ is the surface acceleration on Earth. As the aircraft has to enter and exit the parabolas and catenary curves, a "pull-up" and a "pull-out" maneuver are required before and after each constant-acceleration curve. These maneuvers cause hyper-gravity accelerations from $1.3g$ to $2g$. We also utilized these hyper-g phases for our experiments.

In the parabolic-flight experiments considered here, four different masses of otherwise identical regolith samples were filled in glass cylinders with an inner diameter of 2.5 cm, with cylinder No. 1 having the highest mass and cylinder No. 4 with the lowest mass, respectively.

Even for the largest (1 mm) particles, only 1% of their contact points are with cylinder walls so that the finite cylinder diameter will influence the measurements only through the Janssen effect (Jansen, 1895; Sperl, 2005) described below and quantified in Eq. (1). It should also be noted that the lowermost layer of particles naturally possesses a different filling factor, because of the flat surface of the cylinder base. This boundary effect is relevant for the mm-size particle measurements and was corrected for in the data analysis.

The four glass cylinders were placed in a polycarbonate experimental box and mounted on a linear stage together with a video camera (see Fig. 2). The video camera was used to measure the filling height of each of the samples. Caused by the mounting of the cylinders in the polycarbonate box, their bottom was not visible in the field of view of the camera (see Fig. 2). Therefore, we calibrated the filling-height by comparing the measurements during the $1g$ phases with height measurements on the ground without the box.

During the parabolic flights, we performed two types of experiments.

- Type-1 experiments: The regolith is deagglomerated and homogeneously distributed inside the glass cylinder by a single shake using a succession of an upward $20g$ acceleration, a downward $-20g$ acceleration, and then again an upward $20g$ acceleration so that in the end the sample box comes to rest at its starting position. This initial shaking with an amplitude of 20 cm was performed using the electromagnetic linear stage. Thereafter, the regolith particles sedimented in the ambient (log-g or