REGOLITH DYNAMICS SIMULATIONS OF TEST SCENARIOS FOR COMET 67P/CHURYUMOV-GERASIMENKO.

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Abstract: We study various test scenarios that are aimed at the reproduction of different morphological features observed on comet 67P/Churyumov-Gerasimenko (hereafter 67P) and other small Solar system bodies. For this purpose, we simulate the surface layer regolith dynamics using the discrete element method (DEM). While the immediate objective is to calibrate the mechanical properties of the regolith grains at the particle-particle level such that they imply the macroscopic observables, the long-term aim is to include sublimation and recondensation of volatiles as well as water ice rheology in the simulations in order to better understand outburst triggers and other volatile-related activity.

Introduction: Our overarching aim is to investigate the physics of volatile materials of asteroids and comets. In the present work, we focus on studying a variety of dynamical processes that are implied by morphological features on comet 67P's surface as they were observed by the recently completed ESA cornerstone mission Rosetta [1]. Studying comets is pivotal to a better understanding of the formation and evolution of the Solar system, since the chemical and physical properties of their dust and ice aggregate constituents are directly linked to the nature of the early Solar nebula [2,3]. Rosetta acquired an unprecedented wealth of *in situ* and remote sensing data of the comet's nucleus and coma that we can use to constrain models of the surface-layer particle dynamics. For this purpose, we start by constructing a number of simple test scenarios in order to first calibrate basic mechanical parameters, contact forces, particle sizes, etc., that enable reasonably realistic simulations reproducing observed morphological features and are later needed to investigate more complex scenarios.

Modeling: The simulations are implemented using the open source DEM simulator LIGGGHTS [4]. Generally, we assume the regolith grains to be spheres that consist of a mixture of dust and water ice and that interact according to the Hertz contact model and additionally experience cohesion according to [5]. While this is the way we characterize weakly interacting dust particles, the resulting attraction between grains does not suffice to model the hard consolidated terrain that was found, e.g., at the Abydos final landing site of Philae [6] and that may result from recondensation or sintering. Recondensation in cold layers of water vapor sublimated in warmer layers leads to rigid but breakable bonds between grains. In case of sintering, bonds form between icy grains that, due to solid diffusion, develop necks between them that grow with time, a process that requires neither melting nor extra pressure [7]. In either case, we model this situation by introducing bonds [8] between the particles that can break when the inter-particle forces exceed certain threshold values. Later inclusion of water ice rheology as well as Monte-Carlo-based modeling of sublimation and recondensation of volatiles and Knudsen gas flow through the surface layer will provide us with a tool to research triggers and early phases of outbursts, other cometary activity as well as volatile-related processes on, e.g., main belt objects Ceres and Vesta as observed by the Dawn mission [9].

Test Scenarios: In the following, we introduce a number of test scenarios related to recent observations on comet 67P.

Scenario 1 – Boulder Stability. We start with the simple requirement that boulders of sizes observed on 67P's surface have to be stable without collapsing under their own weight or when falling from small heights. To this end we assume an isolated large spherical boulder to be made up of small polydisperse spherical particles and investigate conditions for it to be stable under the typical surface acceleration on the nucleus or when dropped from small altitudes above a hard surface.

Scenario 2 – Cliff Collapse. Cliffs and overhangs have to be stable, but not so stable as to prevent collapses that were indeed observed on the nucleus surface [10,11,12]. Using a corresponding simulation setup, thermal or dynamical stresses are investigated as possible triggers for collapse. The post-collapse boulder size distribution and angle of repose provide yet further constraints on the inter-particle forces.

Scenario 3 – Wind-Tails. In the next step we investigate the wind-tail-like structures and moats that were observed around many exposed boulders [13,14], see Fig. 1. Based on an analysis using an idealized 3D cellular automaton, these features were interpreted to result from erosion of the surrounding granular surface by an incoming particle stream interacting with the respective boulder [13]. We model this scenario in our DEM framework by introducing a steady randomized stream of small particles colliding with an isolated large spherical boulder in a small-particle bed. Motivated by the suggested global mass transfer from the southern to the northern hemisphere by dust particles emitted in the south during the strong southern near-perihelion activity [15], the incoming model grains are set to move at local orbital velocity on roughly unidirectional horizontal trajectories. In this way we can test whether the simulation can reproduce the observed structures either by erosional or by depositional effects.

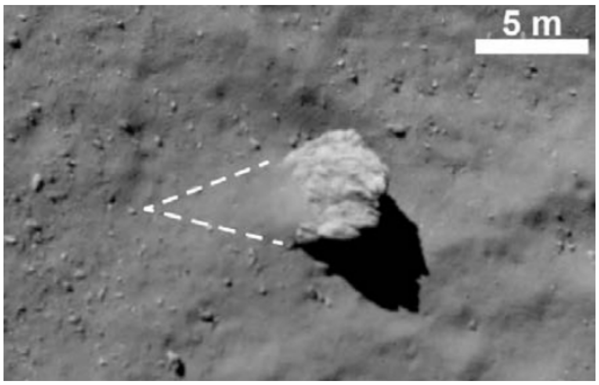

Fig. 1: Boulder (approximately 5 m across) with a wind-tail-like feature (dashed lines) and a moat on the opposite side as imaged by the ROLIS camera onboard the Philae lander. Image from [13].

Scenario 4 – Thermal Fractures. Finally, another interesting scenario serves to study the thermal crack polygons observed in many places where consolidated material is exposed [16]. Using for the uppermost surface layers an external parameterization of temperature in dependence on depth below the surface and on rotational phase, according to a thermal model for a given surface location and heliocentric distance [17], the formation of cracks due to thermal contraction and expansion of the material in presence of spatial and temporal temperature gradients is studied. For this scenario, the bonds between the grains have to lead to a MPa-range macroscopic strength shown to be required for the formation of such fractures [17].

Results: We will show first results of these test scenario simulations by presenting images of the discussed morphological features along with snapshots of the 3D initial model setups and final simulation outcomes, and by reporting constraints on physical parameters and contact forces between regolith particles required to reproduce the features. As an example, Fig. 2 illustrates that the wind-tail scenario can qualitatively be reproduced with our simulations as an erosional process.

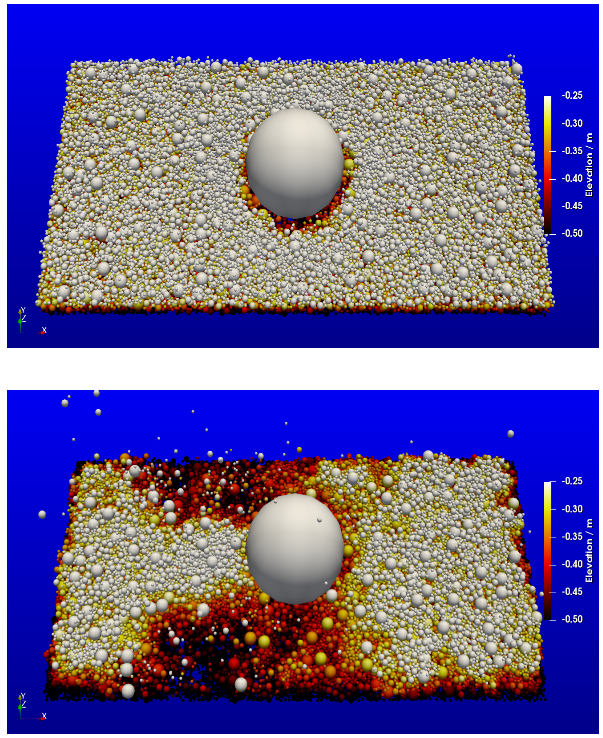

Fig. 2: Top: initial scene of a simulation for explaining the formation of wind-tail-like features. Bottom: final scene after exposure to particle stream from the right side. Like Mottola et al. [13] we find that this scenario is compatible with an erosional process. Color indicates elevation of the particles.

References: [1] Glassmeier K.-H. et al. (2007) *Space Sci. Rev., 128(1)*, 1–21. [2] Skorov Y. and Blum J. (2012) *Icarus, 221*, 1–11. [3] Blum J. et al. (2014) *Icarus, 235*, 156–169. [4] Kloss C. et al. (2012) *Prog. Comput. Fluid Dy., 12(2/3)*, 140–152. [5] Scheeres D. J. et al. (2010) *Icarus, 210*, 968–984. [6] Spohn T. et al. (2015) *Science, 349(6247)*, aab0464. [7] Kuroiwa D. (1961) *Tellus, 13(2)*, 252–259. [8] LIGGGHTS-WITH-BONDS, https://github.com/richti83/LIGGGHTS-WITH-BONDS. [9] Russel C. T. and C. A. Raymond (2011) *Space Sci. Rev., 163(1–4)*, 3–23. [10] Vincent J.-B. et al. (2015) *Astron. Astrophys., 587*, A14. [11] Groussin O. et al. (2015) *Astron. Astrophys., 583*, A32. [12] Pajola M. (2017) *Nature Astronomy, 1*, 0092. [13] Mottola S. et al. (2015) *Science, 349(6247)*, aab0232. [14] Otto K. et al. (2017) *Asteroids, Comets, Meteors ACM2017 Montevideo*. [15] Keller H. U. et al. (2017) *MNRAS, 469*, 357–371. [16] Auger A.-T. et al. (2018) *Icarus, 301*, 173–188. [17] Attree N. et al. (2018) *Astron. Astrophys., in press*, doi:10.1051/0004-6361/201731937.

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