

Studying surface morphologies of comet 67P/C-G using discrete element simulations

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Abstract

We use the discrete element method (DEM) to numerically simulate the surface layer regolith dynamics of comet 67P/Churyumov-Gerasimenko (hereafter 67P/C-G) in order to infer mechanical properties of the surface material.

1. Introduction

Our overarching aim is to investigate the physics of volatile materials of asteroids and comets. To constrain mechanical properties of the surface regolith of comet 67P/C-G, we focus on various morphological features as they have been observed by the Rosetta mission, and aim to reproduce them by DEM modeling of corresponding simulation scenarios. Since the modeling cannot capture the full real-world complexity, the immediate aim is to identify the dominating physical processes involved in the formation of the features and to find a working set of parameters that enables the simulations to be reasonably realistic. The simulation scenarios are then used as starting points for parameter sensitivity studies to constrain mechanical properties, contact forces, particle sizes, etc. of the surface layer material. This is later needed to investigate more complex scenarios like triggers and early phases of outbursts.

2. Numerical modeling

The simulations are implemented using the open source DEM simulator LIGGGHTS [1]. Generally, we assume the surface particles to be represented by poly-disperse spheres consisting of a mixture of dust and water ice. The spheres interact according to the Hertz contact model and additionally are subject to cohesion, friction, rolling friction (also as proxy for more complex particle shapes), and ambient surface acceleration. Furthermore, parallel bonds [2,3] between the spheres can be introduced that break when

the inter-particle stresses exceed certain threshold values. This way, we can also model the hard consolidated terrain that was found at many places on the surface and may result from water ice sintering. To better manage the different size scales of the scenarios and save computational resources to enable the simulation of macroscopic scenarios with relatively small grains, we apply a technique called coarse-graining. Here, instead of individual particles we consider computational parcels of several particles. The model parameters have to be suitably scaled to lead to the same energy density, and evolution of energy density, as for the unscaled system of individual particles [4]. Later inclusion of 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 as well as other volatile-related processes.

3. Discussion of scenarios

We consider four different simulation scenarios related to observations on comet 67P/C-G.

Scenario 1 – Boulder Stability. We start with the requirement that boulders of sizes observed on the nucleus surface have to be stable without collapsing under their own weight or when falling from small heights (e.g. cliffs). For this purpose, we assume a large spherical boulder to be made up of small grains and investigate conditions for it to be reasonably stable when dropped from small altitudes above a hard surface. The boulder totally disintegrates when the bonds are set too weak, whereas too strong bonds leave the boulder undamaged. The bond break threshold is varied until a reasonable behavior is obtained (order of 10-30% of the bonds broken after settling). This provides an order-of-magnitude estimate of the bond strength that is related to the water ice content.

Scenario 2 – Cliff Collapse. Cliffs and overhangs are stable, but not so stable as to prevent collapses that indeed have been observed on the nucleus surface [5,6]. We develop a corresponding simulation setup and vary the bond strength starting with Scenario 1 results. Too weak bonds, while allowing low-level seismic shaking to trigger the collapse, prevent the formation of bouldered debris, whereas stronger bonds enable some bonds to survive the fall but prevent collapse just by the seismic activity. In the latter case we have to introduce artificial cracks to trigger the collapse. The post-collapse boulder size distribution and angle of repose provide further constraints on mechanical parameters.

Scenario 3 – Wind-Tails. Wind-tail-like structures and moats have been observed around many exposed boulders [7,8]. We model this scenario by introducing a steady randomized stream of particles colliding with a large obstacle in a small-particle bed. The incoming model grains are set to move at local orbital velocity on inclined, roughly unidirectional trajectories. To avoid boundary effects, the simulation geometry is set to be periodic in the horizontal dimensions. We obtain a slowly rising equilibrium surface resulting from the local balance between erosion by impacting fast grains and deposition of mobilized slow grains. The obstacle shields the erosion, which results in the formation of a ‘wind-tail’ where deposition predominates erosion. In front of the obstacle, additional erosion by incoming grains reflected at the obstacle can yield a moat. This depends on the shape of the obstacle, the flat front face of a cube being more effective than the rounded shapes of cylinders or spheres that distribute the reflected particles into many directions. Grain sizes, inter-particle forces as well as velocity and inclination of the injected particles affect the equilibrium surface, which enables to infer some of these parameters from observations.

Scenario 4 – Thermal Fractures. Crack polygons have been observed in many places where consolidated material is exposed [9]. They presumably result from stresses induced by spatial and temporal gradients of grain size variations with temperature. For the uppermost surface layers we use 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 [10]. We take ice creep into account by first computing the time-dependence of the horizontal internal stress at given depth as solution to the differential equation that results from continuum

theory by balancing the temperature dependent elastic, thermal, and viscous strain rates [10]. After many comet rotations, this solution becomes cyclic and independent of the initial value, but to be more efficient we instead retrieve the initial value that starts the periodic solution. The radii of the spheres in a bonded particle bed are then scaled such that for the simpler elastic model implemented in LIGGGHTS this induces the correct macroscopic stress field leading to fracture formation, see Fig. 1. Comparison to the spatial scales of crack patterns observed on the nucleus yields information on the material properties.

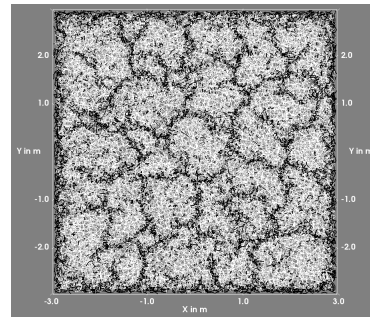


Figure 1: Top view of bond network (white) and broken bonds (black) forming a 1-m-scale crack pattern.

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