1. INTRODUCTION

Cometary nuclei display a wide variety of terrain and geological features, ranging from pits and mountains to flat or terraced regions. The ROSETTA descent images of 67P/Churyumov–Gerasimenko (67P/C–G) show grains of regolith ranging from centimeter sizes to several meters (Mottola et al. 2015). Behind these meter-sized obstacles, wind tails are resolved in the ROLOGS images. Smaller-sized particles as seen by ROLOGS have been observed in orbit by the Osiris instrument (Sierks et al. 2015), suggesting that dust particles contribute to both the cometary tail originating from the nucleus and to the shaping of surface structures. It has been proposed that the wind-tail structures are the result of boulders blocking impinging particles, which otherwise lead to abrasion of the surrounding terrain. No model or explanation for the impinging-particle direction indicated by the wind tails has been given, besides the hypothesis that a particle source exists at some distance (Mottola et al. 2015).

Here, we establish a predictive model for the directions of impinging particles, which does away with a single particle-source and follows the opposite hypothesis: the whole cometary surface acts as source for dust grains. The particular shape of the nucleus in combination with the Coriolis force leads then to prevailing transport directions in specific regions of the comet. The same homogeneous activity model has been applied to dust particles lifted off the mantle with higher velocity and yields excellent agreement with the collimated dust structures seen by Rosetta around 67P/C–G within a few cometary radii (Kramer et al. 2015). The homogeneous surface-activity model works with a minimal set of parameters and assumptions, summarized as follows: (i) incorporation of cometary topography on a scale down to 50 m to ensure a dense and uniform sampling of the entire terrain, (ii) accurate computation of the gravitational potential for the partially concave shape of the nucleus, and (iii) full inclusion of the rotation of the nucleus. In particular, the rotation of the nucleus has a decisive role for establishing dust-transport vectors on the surface and for higher velocities into space. Slower dust trajectories (<1 m s\(^{-1}\)) are strongly affected by the velocity dependent Coriolis force, which pushes particles on circular orbits within a few kilometers around the comet.

2. DUST MOBILIZATION AND TRANSPORT

In a coordinate system attached to the cometary body, the acceleration of a dust particle is approximated by

\[
\mathbf{a}_{\text{dust}}(r) = \mathbf{a}_{\text{gas–drag}} + \mathbf{a}_{\text{grav}} + \mathbf{a}_{\text{centrifugal}} + \mathbf{a}_{\text{Coriolis}}
\]

\[
= \frac{1}{2} C_d \alpha N_{\text{gas}}(r) m_{\text{gas}} (v_{\text{gas}} - v_{\text{dust}}) \mathbf{v}_{\text{gas}} - \mathbf{v}_{\text{dust}}
\]

\[
- \nabla \phi(r) - \omega \times (\omega \times r) - 2\omega \times \mathbf{v}_{\text{dust}},
\]

(1)

which includes the acceleration of dust embedded in the more rapidly expanding gas, the gravitational force, and the effect of centrifugal and Coriolis forces. Additional forces, such as radiation pressure and changes in the rotation period or orientation of the rotation axis are neglected. For instance, the acceleration due to radiation pressure on a 0.1 mm sized spherical dust particle at the perihelion (1.25 AU) is one order of magnitude smaller than the gravitational attraction by the nucleus. We compute the gravitational potential of the irregular and partly concave shape of 67P/C–G by using a 39,996 triangle polyhedral representation. Assumptions are a homogeneous density of the nucleus and a total mass of 10\(^{13}\) kg (Sierks et al. 2015). The polyhedral gravity equations given by Conway (2014) are numerically efficiently implemented, and the dust trajectories are integrated on parallel computing devices using a fourth-order Runge–Kutta integration scheme. In contrast to previous simulations done by Crifo et al. (2005), we fully include the rotation of the comet. In addition, the integration includes the gas–dust interaction, which has been neglected by Thomas et al. (2015). A stationary gas model around 67P/C–G is constructed by assuming homogeneous outgassing activity across the whole cometary surface (Haser 1957), and thermal gas velocity (Huebner et al. 2006, Equation (3.33)),

\[
|v_{\text{gas}}| = \sqrt{\frac{k_B T}{m_{\text{gas}}}}.
\]

(2)

For CO\(_2\) molecules at \(T = 200\) K (Alf-Lagoa et al. 2015), this yields \(|v_{\text{gas}}| = 200\) m s\(^{-1}\). The CO\(_2\) release by 67P/C–G has been detected by the ROSINA instrument on Rosetta at a
the gas surface

Figure 1. Gas density and velocity direction across a slice at \( z = 0 \) km through the cometary nucleus \( (N_{\text{gas}} = 1.4 \times 10^{16} \text{ m}^{-3}) \). The highest gas density is reached in the concave neck region due to gas contributing from both sides of the valley.

effects of changing gas density due to diurnal varying gas pressure are not considered. This limits the model to trajectories lasting less than half a cometary rotation period of about 6 hr. For the derived global dust-transport map, we consider the complete comet as uniformly illuminated and dust emitting. Hence, each trajectory represents a possible dust-transport path over the sunlit part of the surface. The irregular shape of the comet results in collisions with elevated terrain rotating into the pathway. In addition, trajectories are affected by the modulations in the gravitational potential.

3. ANALYSIS OF TRANSPORT VECTORS

The cometary surface is represented by a mesh of 39,996 equal-sized triangles, and each center of a triangle serves as the origin for dust particles. For the simulation, we chose an initial velocity of 0.1 m s\(^{-1}\) along the triangle outward normal to sample particles emitted with less than the escape velocity. The results are independent of the number of triangles used to represent the comet shape and have been reproduced with the 19,806 triangle mesh discussed in Kramer et al. (2015). The maximum gas particle density near the surface is varied from 1.1 \( \times 10^{16} \) to 1.4 \( \times 10^{16} \text{ m}^{-3} \) for particles of density 1000 kg m\(^{-3}\) and radius 0.1 mm, resulting in an overall gas drag very close to the gravitational force. This procedure selects particles hovering up to several hours over the surface. Note that only the overall prefactor \( c_{\text{gas-drag}} \propto N_{\text{gas}}/R_{\text{dust}} \) is of importance for the gas drag, and thus, equivalently, different particle sizes and gas densities are covered in the parametric study. The results shown here for CO\(_2\) hold also for a H\(_2\)O gas atmosphere at \( T = 266 \text{ K} \) with the \( N_{\text{gas}}/R_{\text{dust}} \) ratio decreased by a factor of 1.33 (see Equation (4)).

For a coarse-grained and ensemble-averaged picture, we embed the cometary shape in a volume mesh of cubes with side length 300 m to track particles emitted from several surface triangles. In each cubic subvolume, we establish the average particle momentum direction and assign a total particle momentum of all traversing particles. In addition, the number of particles and the velocities (direction and magnitude) are recorded. The gas-drag forces delay the re-collision of the particle and lead to sustained motion above the surface while the comet rotates. The gas forces are expected to temporarily vary depending on the night/day exposure of the surface. To focus on trajectories across always sunlit terrain, we eliminate trajectories lasting longer than 6 hr (half the rotation period of the comet). We account for the expected downfall of particles caused by a reduction in upward gas drag, for instance, by locally varying outgassing rates, self-shadowing, varying topographical features, and the day–night terminator by taking into account all trajectories up to a ceiling of 300 m above the surface for the surface impinging-particle flux.

4. DISCUSSION OF PREVAILING DUST-TRANSPORT DIRECTIONS

The near-surface vectors for the dust transport are shown in Figure 2, where arrows represent the dust transport (product of velocity and mass) within the mesh cells closest to the surface. The largest dust transfer is predicted in the neck region, despite the homogeneous activity. The reason is the increased outward gas drag above the concave neck due to contributory gas flow from both sides of the valley. This process results in an increased upward acceleration and transfer of dust, despite the
uniform surface distribution of initial dust grains. The same
effect is predicted in Kramer et al. (2015) and observed for the
dust jets forming above the neck region.

Next, we investigate the dust-transport vectors around the area
imaged during the Philae/ROLIS descent, marked by the red
target spheres in Figures 3(c), (f). The viewpoint is chosen to
approximately match the ROLIS image area (Mottola et al. 2015,
Figure S1). We select all trajectories entering the target region to
identify the origins of impinging dust particles. Typical
trajectories are show in Figures 3(b), (e). The dust trajectories
start perpendicular to the local surface, but then move across the
surface and possibly around the lobe due to the cometary
rotation.

Depending on how closely gas drag and gravitational force
cancel each other out, different travel distances and directions
of the grains are predicted. The distribution of trajectory
lengths reaching the target area is given in Figures 3(a), (d). The
trajectories in Figure 3(e) originate at a distance of on
average 1.7 km from the target area along two slightly inclined
main transport vectors. The dust stream indicated by the white
arrow in Figure 3(e) provides a possible source of impinging
particles to explain the direction of the observed wind-tail
patterns by Mottola et al. (2015).

5. CONCLUSIONS

We have proposed a mechanism for predicting dust migration
on the surface of 67P/C–G based on homogeneous dust
emission across the entire surface, linked to a detailed
topographical model of the nucleus. The homogeneous model
yields a minimal-assumption prediction for the temporally
averaged dust transport. Key aspects are the incorporation of
the detailed topography, gravitational potential, and rotational
forces of the comet, leading to global “dust streams” around
67P/C–G. Previous approaches neglect the rotation of the
nucleus due to the small ratio of centrifugal force to gravitational
force and gas drag. For dust transfer, the velocity dependent
Coriolis effect dominates and rotation of the nucleus cannot be
neglected. The predicted transport vectors are in line with the
particle directions inferred from the ROLIS images. The largest
dust transport is expected away from the neck region, caused by
an increased outward gas drag due to the focused transfer of gas
momentum to dust by the concave valley shape. This mechanism
could act in addition to the increased thermal-stress hypothesis
proposed by Alí-Lagoa et al. (2015) in the neck region.

The same homogeneous activity model has been applied to
the near-nucleus coma by Kramer et al. (2015) and is in
excellent agreement with Rosetta NAVCAM observations of
collimated dust jet/structures. The present approach provides a
global and unified theory of dust transfer on the surface and in
the coma, in agreement with Rosetta observations. Addition-
ally, temporarily/spatially isolated sources of activity can be
included in the model, but would require additional parameters
acquired by observations. Future observations by Rosetta are
necessary to map out the global dust transport on 67P/C-G and
compare it with predictions from theoretical models.

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Figure 3. Prevailing dust-transport vectors over the small lobe of 67P/C-G for two different ratios of gas drag/gravity. Panels (a), (d): histogram of trajectory lengths. Panels (b), (e): sample of trajectories reaching a target sphere around the area imaged by Rosetta ROLIS, marked by the red sphere in (c), (f). Panels (c), (f): volume cell averaged transport vectors above the surface. (a)–(c) Gas drag for $N_{\text{gas}} = 1.2 \times 10^{16} \text{ m}^{-3}$ supports short-range transport (mean trajectory length 0.8 km to the target region), while with increased gas drag (d)–(f), $N_{\text{gas}} = 1.4 \times 10^{16} \text{ m}^{-3}$, particles hover over the surface and bridge larger distances (mean trajectory length 1.7 km to the target region). The dust trajectories coincide with the observed wind-tail direction (white arrow in (e)).

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