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Collapse-driven formation of depressions on comet 67P/Churyumov–Gerasimenko

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ABSTRACT

The extremely diverse surface of comet 67P/Churyumov–Gerasimenko contains a large number of depressions or craters of very different scales. Among the most prominent are two large roughly circular depressions, each with radii of several hundred meters. In this work a model for the formation of the depressions is proposed. It is based on the theory of the deformation of a thin circular elastic plate under its own weight. The plate covers a circular cavity with a given radius. The resilience of the plate diminishes over time as a result of its thinning which is itself a consequence of sublimation. When the stress limit is achieved, a gravitational collapse occurs: the plate cracks and the remnants fall into the cavity bottom. A formula that links the radius of the plate corresponding to collapse with the plate thickness has been derived. The formula was discussed for the large intervals of the values of parameters that characterize surface layers of cometary nuclei. It was found that the surface above large cavities collapses sooner than one of a similar thickness that covers a smaller cavity. So, if the collapse mechanism theory works, that larger depressions are therefore older than smaller ones.

1. Introduction

The nucleus of comet 67P/Churyumov–Gerasimenko (henceforth referred to as: comet 67P) has a bilobate shape, with the larger lobe measuring about $4.1 \times 3.3 \times 1.8$ km and the smaller one about $2.6 \times 2.3 \times 1.8$ km (ESA, 2015). The surface features of comet 67P have been the subject of studies by several teams, comprising a number of authors, e.g. Pajola et al. (2015), Thomas et al. (2015), Vincent et al. (2015), Ip et al. (2016) and Krasilnikov et al. (2016). Among the most prominent surface features of comet 67P are two large roughly circular depressions, named Hatmehit and Imhotep on the smaller and larger lobe respectively According to Krasilnikov et al. (2016) they have a diameter of (957 ± 71) m and 630 m and a depth to diameter ratio of 0.12 and 0.28. Krasilnikov et al. (2016) considers Hatmehit, Imhotep and 17 other depressions and crater-like forms as likely candidates for impact craters. The size-frequency distribution of the circular depressions with sizes (0.15 – 1) km with a steep-wall and a flat bottom on the nucleus surface of 67P was studied by Ip et al. (2016). The increase in the diameter of the cylindrical depression on the surface of 67P due to the sublimation of the walls was modeled by Kossacki et al. (2006).

According to observations nucleus of comet 67P looses on average a layer of about 1 ± 0.5 m thick per one orbital period (Bertaux, 2015). This value is more or less typical for all cometary nuclei. However, the local recession rate may be considerably nonuniform. The recession rate of a surface that is covered by dust was recently simulated for various locations on comet 67P (Kossacki et al., 2015, 2016). Taking recession of the surface into account two main possible mechanisms for the formation of the depressions were proposed. They are the *non-uniform erosion of the surface due to sublimation of ice* (Mousis et al., 2015) and the *gravitational collapse of a porous material overlaying a void* (Pajola et al., 2015). Mousis et al. (2015) have found that the subsurface of 67P is not uniform at a spatial scale of ~(100 – 200) m. Similar conclusion were provided by the CONSERT experiment both on board of the Rosetta mission and on its lander Philae (Kofman et al., 2015). Vincent et al. (2015) studying the active pits on 67P concluded that 'the size and special distribution of pits imply that large heterogeneities exists in the physical, structural or compositional properties of the first few hundred meters below the current nucleus surface.' Thus the internal cavities (empty spaces) could be responsible for the heterogeneity of the nucleus. It is important to note that this opinion is contrary to those previously held: Pätzold et al. (2016), on the basis of studies on the gravity field of the nucleus of 67P, concludes that its interior is homogeneous and constant in density on a global scale. However the opinion of Pätzold et al. (2016) concerns homogeneity purely on the global scale, but other papers accept the existence of smaller heterogeneities.

Britt et al. (2004), Pajola et al. (2015), and Vincent et al. (2015) present phenomenlogically plausible scenario for the forma-

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tion of the depressions. Vincent et al. (2015) states: ‘we propose that the pits are formed via sinkhole collapse, when the ceiling of a subsurface cavity becomes too thin to support itself’. From the static point of view it does not matter what the exact process is that leads up to the loss of the equilibrium of the cover plate: two processes can act simultaneously. The first concerns the mechanism of the sinkhole during which there is an increase in the size of cavity, due to a process of internal sublimation; the second concerns the process of sublimation from outer surface of the cover plate. When the surface of the nucleus retreats due to sublimation, the subsurface cavity loses its ceiling and the cavity becomes the depression. The last stage of this process progresses rapidly with the collapse of the, now thinned, ceiling. This process has not, as yet, been observed on 67P However, the on-going evolution of certain surface features on 67P has been well documented by the Rosetta mission. An example is the morphological changes that are clearly visible on the surface, and which have roundish features. They grew in size at a rate of $(5.6 – 8.1)\times 10^{-5}$ m s^{-1} (a few meters per day) during a period of observation between 24 May 2015 to 11 July 2015 (Groussin et al., 2015). For comparison: in the conclusion of this paper it is mentioned that the observation of a nucleus that spans over a few orbital periods (∼10, or so) would be sufficient to observe a collapse.

The author of this paper is unaware of any quantitative model concerning the gravitational collapse of the cometary surface-forming material onto a cavity lying below. In this paper there is considered a model of the formation of the depression as a consequence of the collapse of sublimating icy-dusty consolidated material overlying the sub-surface cavity. Consequently, the model requires some primordial existence of the sub-surface cavities or at least a fairly recent formation of the cavities. These may be either randomly located within the nucleus, in which case they may be of primary origin or they may be formed below the surface as a result of the outflow of sublimed material through the local vents.

The origin of circular depressions on the cometary surfaces is an enigma since they were first observed following relatively close approaches to the cometary nuclei. The morphological form of the cometary depressions is considerably different from that of the impact craters, raising the question, how were the depressions formatted? A serious attempt to answer that question was became a possibility when surfaces of the comet 19P/Borelly and 81P/Wild were observed in 2001 and 2004. Britt et al. (2004) analyzing surface structures in comet 19P/Borelly were the pioneers of the idea of collapse-driven origin of circular depressions on comets.

At the end of this section let me cite the opinion of Besse et al. (2015) who states that the actual origin of depressions on comet 67P is still unknown. Thus, farther studies are required.

2. Mathematical model

The formation of depression due to the gravitational collapse of a consolidated layer covering cylindrical cavity is here considered. The layer is assumed to be a uniform cylindrical flat plate with the radius R equal to that of the cavity, with the thickness h and with the density ρ. We consider the breaking and the subsequent collapse of the layer above the cavity to be a static problem. After the depression is formed, following the collapse, its depth is equal to the depth of the cavity minus that of the layer of the fallen rubble. The forces acting on the plate are its weight, its intrinsic strength, and the gas pressure of gases. Once the strength limit of the material comprising the plate material has been reached, a collapse is imminent, and the rubble falls into the bottom of the cavity.

An icy-dusty plate above the cavity is assumed to be composed of an elastic material. Any more realistic model (e.g. elasto-plastic model) is beyond the scope of this study. The model considered below assumes that the plate over the cavity is thin, $h/R \ll 1$. If so, the results given by the theory of the deformations of thin elastic plates can be applied. The problem under consideration is axially symmetric: a circular plate, covering cylindrical cavity, has its center on the axis of the cavity. The middle surface of the plate in its initial undisturbed state is on the level of $\zeta = 0$. From the formal point of view the “initial undisturbed state” corresponds to situation when the gravitational field is switched off, $g = 0$, and the pressure exerted on the plate $p = 0$. Landau and Lifshic (1958) give a formula for vertical displacement $\zeta = \zeta(r)$ of the points belonging to the middle surface of the plate:

$$\zeta = \beta\left(R^2 - r^2\right)\left(AR^2 - r^2\right) \tag{1}$$

Here r is the distance from the center of the plate. Formula (1) depends on two parameters β and A. Parameter β is:

$$\beta = \frac{3g\rho\left(1-\nu^2\right)}{16h^2E} \tag{2}$$

Here ρ, ν, and E are the density, the Poisson ratio, and the Young modulus of the plate material. Parameter A depends on the model of fixation of the plate above the cavity. Two possibilities for the boundary conditions on the circular edge of the plate ought to be considered:

(i) The edge of the plate is fixed on the cavity edge, *or*
(ii) The edge of the plate is located free of the cavity edge beyond the limit of the cavity.

These requirements make it impossible to fall down the deformed plate into the cavity. The case (i) seems to be more relevant to cometary nucleus then the case (ii). According to Landau and Lifshic (1958) there is

$$A = 1 \quad for\ case\ (i), \quad \text{and} \quad A = \frac{5+\nu}{1+\nu} > 1 \quad for\ case\ (ii). \tag{3}$$

Formula (1) for displacement $\zeta = \zeta(r)$ supplemented by formula (2) for parameter β and by formula (3) for parameter A allow for the consideration of the deformation of any segment of a meridianal line on the plate. Deformation is understood as the relative lengthening Δ of a distance measured along a meridional line on the middle surface of the plate and is equal to

$$\Delta = \left[\sqrt{(dr)^2 + (d\varsigma)^2} - dr\right]/dr = \sqrt{1 + (d\varsigma/dr)^2} - 1. \tag{4}$$

The plate, initially flat, becomes deformed as a result of its own weight: it takes the shape of the axial-symmetric dome convexes downward direction. This is the case only if the cavity has a radius R smaller than R_{crack} (that is the radius when cracking occurs). If $R > R_{crack}$ the plate collapses, leaving the broken remnants (these are from within the circle with radius $r_{crack} < R_{crack}$) on the bottom of the cavity, and forming a collar that is joined at its upper part with the edge of the cavity, see Fig. 1. This cracking and breaking scenario is correct provided that the plate weight per unit of its surface ρgh is sufficiently greater than the pressure of gas filling the cavity. The fate of the collar is not considered here. The radius r_{crack} corresponds to the deformation equal to Δ_{crack}. The plate material from the region within the circle with radius r_{crack} collapsed onto the bottom of the cavity. The material from the ring (r_{crack} – R_{large}) forms a collar that is attached to the cavity rim. The fate of the collar (whether it remains hanging on the cavity edge or collapses to the bottom) is beyond the scope of this study.

Deformation Δ takes its maximum value Δ_{max} in the point r_0 of the displacement line $\zeta = \zeta(r)$ where the derivative $d\zeta/dr$ assumes its maximum value, which is in the point where $d^2\zeta/dr^2 = 0$. This condition gives

$$r_0 = \left(\frac{A+1}{6}\right)^{1/2} R. \tag{5}$$