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Structure and elastic parameters of the near surface of Abydos site on comet 67P/Churyumov–Gerasimenko, as obtained by SESAME/CASSE listening to the MUPUS insertion phase

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ABSTRACT

The accelerometers of the SESAME/CASSE instrument aboard Rosetta's lander Philae recorded surface waves produced during the MUPUS hammering phase. After presenting evidence that all feet of Philae were in contact with the ground, we analyze group arrival time differences between the three feet of Philae and obtain a Rayleigh wave velocity between 79 m s^{-1} and 400 m s^{-1}, which translate into a shear modulus μ of 3.6 MPa $\leq \mu \leq$ 346 MPa, and a Young's modulus E of 7.2 MPa $\leq E \leq$ 980 MPa (with the lower bounds being better constrained than the upper bounds). Mixture models of snow and regolith suggest a porosity below 0.74. From the frequency-dependent dispersion of the average signal we conclude that the above values are valid for a surface layer of 10 cm to 50 cm thickness, while rigidity is significantly reduced underneath this layer. Our findings are consistent with the concept of a thin consolidated shell around a less rigid interior.

1. Introduction

Comets are commonly considered to consist of largely unaltered, if not pristine, remnants from the origin of the solar system. However, their activity, the very property that defines comets as a class of objects, constitutes an alteration of the surface material, as some fraction of it is blown into space while another fraction remains on the cometary surface.

When Whipple (1950) suggested that comets might be a conglomerate of ices and meteorite-like materials, he immediately drew the conclusion that there must be a limiting size discriminating dust particles that are blown away from those that remain on the surface, and that the different volatiles might produce layers based on sublimation properties. The observation that the surface of 1P/Halley is very dark and widely inactive even close to perihelion (Keller et al., 1986) gave rise to a series of models about the formation of inert mantles and crusts on the surface of comets that would be capable to locally suppress cometary activity (a brief review of the status of the debate at the time when the Rosetta project started is given by Kührt & Keller, 1994).

Several effects and processes may be involved in the modification of the cometary surface, and lead to a range of results, as can be illustrated by two examples: Prialnik & Mekler (1991), for example, predict the formation of an ice crust with increased density and a thickness of the order of 1 m underneath a dust mantle (with unspecified mechanical properties) of a few millimeters within the time period of a few tens of cometary orbits. Kührt & Keller (1994) note that cohesive forces also exist between conglomerates of the dust and that a crust consisting of both ice and dust might be as thin as 10 cm, but might also reach several meters in thickness.

The role of water vapor diminishes when comet surface temperature decreases after perihelion. As Thomas et al. (1994) point out, ice particles at 253 K sinter within a few days due to vapor deposition, but below 30 K, the relevant process is the diffusion of water molecules along the particle surface. With this mechanism,

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the formation of a sinter bridge of 10% particle radius will take thousands of years for a 0.1 μm ice particle, but hundreds of millions of years for 1 μm particles. It should be pointed out here that water vapor deposition could also affect dust layers by cementing even water free silicate grains that are not subject to diffusion of individual molecules along the surface, and which are impossible to sinter under comet conditions.

In the late 1980 s and early 1990 s, a series of thermal vacuum experiments were carried out in the 46 m^3 space simulation chamber at the German Aerospace Centre (DLR) in Cologne. The goal of these KOSI (in German *Ko*meten *Si*mulation) experiments was to investigate the evolution of cometary analog materials (mixtures of H_2O and CO_2, and olivine powder) under periodic illumination, ablation, and deposition. The large chamber allowed not only to well separate samples from chamber walls, but also to perform e.g. mechanical measurements of surface strength without opening the chamber.

Experiments from the KOSI series show the formation of crusts on time scales of days: Kochan et al. (1989) report the formation of a 7 mm surface layer due to strengthening of bridges between ice grains by water recondensation in KOSI-3 and KOSI-4 experiments. Grün et al. (1993) report from the KOSI-9 experiment not only the formation of dust covers that suppress the sublimation of water ice, but also the reactivation of inert surfaces by avalanches that remove these dust covers.

In the light of these results, the experimental determination of elastic properties of the cometary surface material as well as of a possible layering were defined as goals of CASSE (Comet Acoustic Surface Sounding Experiment, Seidensticker et al., 2007), to be executed *in situ* on the surface of a comet. The current contribution focuses on two questions:

a) Is the surface material layered, and what are the layer thicknesses?
b) What are the characteristics of the discernible layers in terms of shear wave velocities and shear modulus (rigidity)?

The means to answer these questions is the interpretation of the propagation velocities and frequency dependent dispersion of elastic waves generated by a hammering device (MUPUS, a thermal probe and strength sensor on Rosetta's lander Philae) and recorded with the accelerometers of CASSE. The whereabouts of these instruments in deployed configuration are shown in Fig. 1, a description of the technical details of the experiments is given by Knapmeyer et al. (2016a and b, both together will be termed Paper I hereafter).

We will not, however, undertake a detailed comparison of our results with the models presented in the literature since the last apparition of Halley, because this would require an extensive review.

In the next section we summarize published properties of comet 67P/Churyumov-Gerasimenko (67P/C-G for short) as far as they are relevant for the interpretation of CASSE data resulting from the MUPUS listening experiment in terms of material properties. The subsequent Section 3 introduces the assumptions made to define a model material, and analog materials that may be used with mixing theories to obtain such a model material. We further introduce the methods used for processing and interpretation of CASSE data. Section 4 briefly describes the experiment conducted on 67P/C-G, as well as its limitations, and additional experiments carried out on ground to better understand the mode of ground contact of Philae. All cometary results are presented in Section 5 and interpreted in terms of material parameters, composition and structure in Section 6. In Section 7 we finally present a synthesis of results found in the literature with our results.

2. Comet 67P/Churyumov–Gerasimenko

On November 12, 2014, at 15:34 UTC, the lander unit Philae of ESA's cornerstone mission Rosetta landed on comet 67P/Churyumov-Gerasimenko, 112 m from the planned landing site Agilkia (Biele et al., 2015). The visit to Agilkia was however brief (but nevertheless returned data on mechanical properties from the surface contact, Möhlmann et al., 2017), and after bouncing off and additional two hours of uncontrolled drift across the comet, the lander finally found rest at a place named Abydos later on. Philae could be located using the CONSERT radar (Comet Nucleus Sounding Experiment by Radio-wave Transmission, Herique et al., 2015). In September 2016, only a few weeks prior to the deorbiting of Rosetta, Philae was discovered on a series of OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System, a narrow and a wide angle science camera system onboard the orbiter) images, perched under an overhang in rather rough terrain (Ulamec et al., 2017).

Comet 67P/Churyumov–Gerasimenko (a.k.a. 1969 h, 1969 IV, or C/1969 R1, 67P/C-G) was listed already by Schwehm (1989) as one of the four possible and design-driving targets of Rosetta. The result of further studies and downselection was that 67P/C-G and two other candidates were abandoned in favor of 46P/Wirtanen (Schwehm & Schulz, 1999), but it became the ultimate target again after an Ariane launch vehicle failure in 2002 and subsequent grounding of Rosetta in 2003 (Glassmeier et al., 2007). 67P/C-G was first noticed on a photographic plate exposed on September 11, 1969, and shortly afterwards identified by K. Churyumov and S.V. Gerasimenko on four more plates taken in the same month (Churyumov, 2004). It was found quickly that this comet had a close encounter (0.052 AU or 7.7×10^6 km) with Jupiter on February 4, 1959, which shifted its perihelion from 2.75 AU to 1.28 AU and reduced its period from nine years to approx. 6.5 years (Churyumov & Gerasimenko, 1972, and references therein). The extension of the backward computations by Maquet (2015) confirms that this encounter changed all orbital parameters significantly: eccentricity was nearly doubled, while the inclination was reduced by more than 10°. The previous Jupiter encounter on October 2, 1923, was less close (0.92 AU) and had a smaller effect. Backtracking 67P/C-G further into the past proved impossible due to the chaotic behavior of the system.

The type of orbit modification experienced by 67P/C-G was one of the criteria used by Wood (1987), who compiled a list of 43 comets as possible targets for a sample return mission: the comet should have a perihelion within reach for a spacecraft, but should have had a different, farther out orbit in the recent past such that it was not warmed and thus modified too much by the sun. One of Wood's candidates is 67P/C-G, which up to now witnessed only nine perihelion passages on its current orbit, including the one accompanied by the Rosetta mission.

2.1. Bulk mass and density

The mass of 67P/C-G is determined by the Rosetta Radio Science experiment RSI from spacecraft tracking and Doppler shift analysis to be $M_{67P} = (9.982 \pm 3) \times 10^{12}$ kg. Division by the comet volume of approx. 18.7 km^3 yields a bulk density of the whole body of $\rho_{67P} = (533 \pm 6)$ kg m^{-3} (Pätzold et al., 2016 and references therein). With the density of ice, a lower limit of the bulk porosity φ_{bulk} results. Pätzold et al. (2016) assume that amorphous ice with a density of $\rho_{amorph} = 940$ kg m^{-3} dominates and give a lower limit of 45 % for the porosity. With the minimum density of hexagonal crystalline ice *Ih*, $\rho_{Ih} \geq 916$ kg m^{-3} (according to the International Association for the Properties of Water and Steam, 2009, equation of state for $p = 0$ *Pa*, $T = 273$ *K*), and without dust, $\varphi_{bulk} \geq 41.8\,\%$ results.