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# Shape and obliquity effects on the thermal evolution of the Rosetta target 67P/Churyumov–Gerasimenko cometary nucleus

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ABSTRACT

This work is dedicated to the application to 67P/Churyumov–Gerasimenko of a new quasi-3D approach for non-spherically shaped comet nuclei with the aim to interpret the current activity of the comet in terms of initial characteristics and to predict shape and internal stratification evolution of the nucleus. The model is applied to differently shaped nuclei taking into account the characteristics of Comet 67P/Churyumov–Gerasimenko deduced from observations. We focus our attention on the combined effects that shapes and obliquity have on the comet surface and sub-surface evolution. We discuss the results in terms of activity, local dust mantle formation and disruption, erosion of the surface and internal stratigraphy.

The results show that differently shaped nuclei can have different internal structures leading to different activity patterns and behaviors. Our calculations have shown that local variations in the dust and gas fluxes can be induced by the nucleus shape. The distribution of "active" areas on Comet 67P/Churyumov–Gerasimenko is different because of different shapes, reflecting the illumination conditions on the surface. These shapes can influence the structure of the inner coma, but the coma far away from the nucleus is only marginally affected by the nucleus shape. However, different comet behaviors can arise from differently shaped comet nuclei, especially in terms of local activity, surface and sub-surface characteristics and properties. The water flux local distribution is the most influenced by the shape as it is directly linked to the illumination. Irregular shapes have large shadowing effects that can result in activity patterns on the comet surface.

The effects of different pole directions are discussed to see the relations with the nucleus activity and internal structure. It is shown that the orientation of the rotation axis plays a strong role on the surface evolution of 67P/Churyumov–Gerasimenko, determining seasonal effects on the fluxes. The activity of the comet changes greatly with the nucleus obliquity leading to pre–post-perihelion differences in the activity and seasonal effects. The effects of the dust deposition and crust formation on the cometary activity have also been simulated and are discussed with respect to 67P/Churyumov–Gerasimenko observations. The dust mantling is also strongly obliquity dependent, with different surface distributions of the dust-covered regions according to the different comet pole orientations. Finally, we show that our model can reproduce the fluxes behavior near perihelion in terms of amplitude and asymmetry, and we estimate 20% of the illuminated surface to be active.

## 1. Introduction

Comet nuclei are considered as the most pristine bodies of the Solar System, and consequently their study sheds an important light on the processes occurring during the initial stages of the Solar System formation. Rosetta's main objective is to rendezvous Comet 67P/Churyumov–Gerasimenko. The spacecraft will study the nucleus of the comet and its environment, from the onset of the activity near the aphelion to the maximum of activity near perihelion, giving thus insights both on its origin and on its evolution, with particular care devoted to its thermal evolution (for a review, see e.g. Glassmeier et al. (2007)).

Comet nuclei are very difficult to observe, and no direct data of their interior are presently available (with the sole and arguable exception of the data on the ejecta resulting from Deep Impact's experiment, e.g. Kadono et al. (2007) and A'Hearn et al. (2005)). However, theoretical models of the chemical differentiation and

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thermal evolution of a nucleus can be used to link coma observations with the characteristics and properties of real nuclei.

In order to prepare adequately the arrival and the landing of the Rosetta mission, both long distance observations and numerical models of the nucleus and its activity are required. Predictive models of the thermal evolution and differentiation of a cometary nucleus are needed to understand the nature of the comet nuclei in terms of composition, structure and physical properties, to understand the physical phenomena that can occur in comet nuclei and foresee cometary activity.

Numerical models of comet evolution have been developed during the last two decades, starting from relatively simple one-dimensional representation of an ideal spherical nucleus (Fanale and Salvail, 1984; Herman and Podolak, 1985; Espinasse et al., 1991; De Sanctis et al., 1999, 2001) to the more complex models presently available, which take into account both the latitudinal and the longitudinal variations of illumination (Capria et al., 2001; Cohen et al., 2003; De Sanctis et al., 2005, 2007; Sarid et al., 2005; Rosenberg and Prialnik, 2007). Most of these models deal with spherical nuclei, but the recent in situ measurements of comet nuclei have shown typical non-spherical shapes and particular topography including large depressions and mountain-like features. The images of the nuclei of Comet 1P/Halley from Giotto (see e.g. Keller et al., 1986), Comet 19P/Borrelly observed by Deep Space 1 (Oberst et al., 2004), Comet 81P/Wild 2 and 9P/Tempel, from Stardust and Deep Impact, have confirmed these views.

Studies of the thermal and chemical evolution of cometary nuclei have shown the importance of topography (Colwell, 1997; Gutiérrez et al., 2000, 2001; Lasue et al., 2008). Gutiérrez et al. (2000, 2001) have shown that topographic features of comet nuclei increase the global water production along the orbit. They can also be at the origin of jet-like structures (see e.g. Crifo and Rodionov, 1997) as well as the main contributor to the oscillations of the comet's light-curve. Since the shape of the comet nucleus affects its thermal evolution and vice versa (Cohen et al., 2003), it is mandatory to develop a model that takes into account the non-spherical shape of the observed comets and their evolution with time.

We applied the model described in Lasue et al. (2008) to the case of Comet 67P/Churyumov–Gerasimenko. This new approach is suitable to describe non-spherically shaped comet nuclei with the aim to interpret the current activity of comets in terms of initial characteristics, and to predict the shape and internal stratification evolution of the nucleus.

## 2. Comet 67P/Churyumov–Gerasimenko

Comet 67P/Churyumov–Gerasimenko was discovered in 1969, and it belongs to the Jupiter family. Its dynamical history has been studied by Beliaev et al. (1986) and Carusi et al. (1985). They found that the comet had close encounters with Jupiter in 1840 and 1959 that changed the perihelion distance significantly. From 1600 to 1959, both the perihelion and aphelion distances of the comet (respectively, $q$ and $Q$) increased, while its inclination $i$ continued to decrease slightly. Then, a significant reduction in both $q$ (from 2.7 to 1.3 AU) and $i$ (from 28° to 7°) occurred, followed by a complete reorientation of the nodal line. These events probably triggered an extra activity of the comet, leading to its discovery in 1969. The present orbit is characterized by a period of 6.57 years, $q = 1.292$ AU, $e = 0.632$ and $i = 7.12°$. The comet has now completed only 7 perihelion passages on its new orbit.

67P/Churyumov–Gerasimenko has been poorly observed before it was designed as the target of the Rosetta mission in 2004. In the last few years, the comet was the subject of many observations and theoretical work, which improved our knowledge of its characteristics.

The comet radius has been estimated with different techniques. From HST observations, it seems to be about 2 km, in agreement with the radius estimated by ground-based observations (Mueller, 1992; Kamoun et al., 1998; Tancredi et al., 2000). Radar observations (Kamoun et al., 1998) give an upper limit of 3.7 km for the nucleus radius.

Using Spitzer Space Telescope, Lamy et al. (2008) derived an ellipsoid with the principal axes of 4.40–5.20 km, 4.16–4.30 km and 3.40–3.50 km, corresponding to an effective spherical radius in the 1.93–2.03 km range and an albedo in the 0.039–0.043 range.

From the HST observations of the comet light-curve, it is possible to invert a shape model of the comet by making the assumption of a surface albedo equal to 0.04 and constraining the principal axis of the inertia tensor (Lamy et al., 2007). These shape models present relatively large variations of the shape of the comet and are characterized by the presence of 'mountains' the size of half the radius of the equivalent ellipsoid discussed earlier. Such irregularities have not yet been seen in cometary nuclei but could in principle exist due to the small self-gravity of these objects.

The rotation axis of 67P/Churyumov–Gerasimenko has been estimated in different ways. Chesley (2004) estimated that the spin axis is about $(I, \Phi) = (43°, 236°)$ (where the obliquity $I$ is the angle between the orbital and equatorial planes of the comet, and $\Phi$ is measured from the vernal equinox of the comet, counter-clockwise). Schleicher (2006) studied the coma morphology on images taken in early 1996 and concluded that the geometry of the features could be explained if $(I, \Phi) = (46°, 262°)$, or if the rotation is retrograde $(I, \Phi) = (134°, 82°)$. This solution is similar to that of Chesley (2004). Davidson and Gutierrez (2005) using non-gravitational forces modeling found a solution where $\Phi$ is 60° ± 15° or 240° ± 15°, and $I$ is between 100° and 140° for $\Phi \approx 60°$, or in the range 40–80°, if $\Phi \approx 240°$. According to Lamy et al. (2007), the rotation axis is located at RA = 220° ± 50° and Dec = −70° ± 10° (retrograde rotation). However, there is still very large uncertainty on the pole direction of this comet.

A dust trail was detected in the Spitzer/MIPS images when the comet was at 4.5 AU post-perihelion (Agarwal et al., 2007; Kelley et al., 2009). Because of its dust trail, 67P/Churyumov–Gerasimenko is known as a comet that emits large dust particles (Agarwal et al., 2007). The dust grains greater than 1 mm are not sensitive to solar radiation pressure and may remain in the vicinity of the nucleus. In 2003, 67P/Churyumov–Gerasimenko's appearance was quite intriguing. The comet exhibited a thin, bright dust cloud, which has been the subject of some controversial interpretations. Some observers inferred that the thin dust cloud could be composed of dust released around the previous perihelion passage on January 1996. Fulle et al. (2004) concluded that the thin bright cloud was composed of the dust particles ejected more recently, in the period approximately 150 days before and after the perihelion. Moreno et al. (2004) used the same approach and argued that the thin cloud is not a dust trail. Therefore, it is likely that the thin bright cloud observed in early 2003 is the neckline structure. According to the recent work by Ishiguro (2008), the dust trail is composed by particles quite large (up to 5 mm in radius) released during the 2002/2003 apparition. Production rate measurements of five species are available for 67P/Churyumov–Gerasimenko: OH, CN, C2, C3 and NH. All these species were detected during both the 1982 and 1996 apparitions. The data on the water production rate, spanning a large range of heliocentric distances, reveal a pre–post-perihelion asymmetry, with peak productivity occurring 1 month after perihelion passage (Agarwal et al., 2007; Lamy et al., 2007).