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Modelling the evolution of a comet subsurface: implications for 67P/Churyumov–Gerasimenko

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ABSTRACT

Modelling the evolution of comets is a complex task aiming at providing constraints on physical processes and internal properties that are inaccessible to observations, although they could potentially bring key elements to our understanding of the origins of these primitive objects. This field has made a tremendous step forward in the post-*Giotto* area, owing to detailed space- and ground-based observations, as well as detailed laboratory simulations of comet nuclei. In this paper, we review studies that we believe are significant for interpreting the observations of 67P/Churyumov–Gerasimenko by the ESA/*Rosetta* mission, and provide new calculations where needed. These studies hold a strong statistical significance, which is exactly what is needed for this comet with an orbital evolution that cannot be traced back accurately for more than hundreds of years. We show that radial and lateral differentiation may have occurred on 67P's chaotic path to the inner Solar system, and that internal inhomogeneities may result in an erratic activity pattern. Finally, we discuss the origins of circular depressions seen on several comets including 67P, and suggest that they could be considered as evidence of the past processing of subsurface layers.

Key words: methods: numerical – comets: general – comets: individual: 67P/Churyumov–Gerasimenko.

1 INTRODUCTION

Comets may be the best preserved objects in the Solar system, although this statement does not mean that their properties, as we observe them today, have been entirely preserved for the age of the Solar system. Indeed, being made of volatile species which are very sensitive to temperature changes, any modification in the energy budget of a given comet would result in modifications in their composition and internal structure. These modifications need to be understood and constrained in order to decipher the clues that comets hold on the formation of the Solar system. These modifications however may not be directly accessible to observations, as these would provide constraints on the surface at best, so that models – which use surface characteristics as boundary conditions – must be applied to assess the physical processes and internal properties that are indeed inaccessible to observations. The field of modelling comet nuclei made a tremendous leap forward after the detailed observations of comet 1P/Halley by the ESA/*Giotto* mission, and the KOSI experiments performed around the same time, from 1987 to 1993. The KOSI experiments were undertaken to simulate the behaviour of comets in a space-like environment (under very low pressure and low temperature conditions), as summarized by Sears, Kochan & Huebner (1999) and Huebner et al. (2006). They were designed to study sublimation and heat transfer in porous ice and dust mixtures. They demonstrated that the energy transported by water vapour is an important contribution to the heat balance. Though the idea was initially suggested by Smoluchowski (1982), it was verified in the KOSI experiments (Spohn & Benkhoff 1990; Benkhoff & Spohn 1991), which showed that in fact, in a porous matrix, heat transport into the interior by the vapour phase is more effective than heat conduction by the matrix. Also, they showed that sublimated gas can escape from the surface, but can also recondense after migrating towards the interior of the samples. Eventually, the experiments showed that the sublimation of volatiles causes a chemical differentiation of the samples studied. This includes also the formation of a dust mantle at the surface of the samples.

These experiments, along with those carried out – and still performed today – by different groups, have been the basis of theoretical models of comet nuclei. Increasingly sophisticated models, which account for processes expected to dominate the evolution of comets such as layering of the internal composition, uneven

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erosion of nuclei, or dust mantle formation, have been able to reproduce the activity pattern of most comets. On the one hand, this is impressive considering the complexity of mechanisms involved, the uncertainties regarding values of thermo-physical parameters, and the limited direct evidence gathered on the nature of cometary material. On the other hand, after 30 yr of thermal evolution modelling, questions as to whether and to what extent comets may be pristine are still open. In this context, the detailed study of 67P/Churyumov–Gerasimenko (67P hereafter) by the ESA/*Rosetta* mission has revealed that the physical processes involved in comet evolution are indeed very complex, and that disentangling primordial properties from expected evolutionary patterns may be more difficult than we had previously envisioned. In this paper, we review some works that we find significant for interpreting the observations of 67P. These works were not necessarily developed for 67P in particular, but they are of theoretical significance. They emphasize the importance of radial differentiation of the physical and chemical properties after the long-term processing of comet nuclei on their orbital evolution from the outer Solar system reservoirs to their current orbits (reviewed in section 2), as well as the lateral chemical differentiation that may occur if surface inhomogeneities are present (reviewed in Section 3). Then, whether one believes that non-uniform compositions are primordial, evolutionary, or a combination of both, the fact remains that the presence of internal inhomogeneities does have an effect on the activity of a comet, as reviewed in Section 4. Finally, we review in detail the models meant to interpret the existence of a particular feature at the surface of 67P, namely circular depressions. We provide new calculations which show that these features cannot have been formed on 67P's current orbit so that they may provide a proof of the past thermal processing of this comet.

2 THERMALLY INDUCED STRATIFICATION

2.1 Thermal processing at large heliocentric distance

Constraining the thermal processing of nuclei in the two main reservoirs (the Oort Cloud or the Kuiper Belt/Scattered Disc) requires some knowledge of the comet formation process. However, as recently discussed by Davidsson et al. (2016), the formation of comets is still a subject of fierce debate. Therefore, studying the early thermal evolution of comets is only speculative, given the current lack of constraint on their formation mechanism, formation time, time-scale and location. In principle, short-lived radioactive nuclide ^{26}Al should be effective in heating a comet interior, although only for a limited period of time after the formation of Calcium-Aluminum-rich Inclusions (CAIs). Therefore its action should be considered in scenario where comets are formed fast and shortly after CAI formation. Nonetheless, long-lived isotopes like ^{40}K, ^{23}U, ^{238}U or ^{232}Th would still need to be accounted, whatever the formation scenario, especially when studying the survival of super volatile species like CO or N_2, as they would inevitably generate a more moderate but more sustained heating of comet nuclei, and therefore play a significant role in differentiating their largest parent bodies. The main expected outcomes of radiogenic heating of comet nuclei, described for example by Prialnik, Bar-Nun & Podolak (1987), Prialnik, Brosch & Ianovici (1995) or Prialnik & Podolak (1995) can be summarized as follows: (1) pristine comet interiors could have been thoroughly preserved, (2) some comet interiors could have been partly to completely crystallized, except for a negligible outer layer which might have remained primitive, (3) some nuclei could have developed a 'differentiated' structure, with a crystallized core, a layer of condensed volatiles, and pristine outer layers made of unaltered material. We stress again that given the current lack of constraints on the formation mechanism of comets, the effects of radiogenic heating are speculative, so are the effects of early collisions, in particular during the accretion phase. However, when accounting for both sources of heat (radiogenic and accretional), the occurrence of high internal temperatures and production of liquid water would be strengthened, as demonstrated by Merk & Prialnik (2006), who showed that liquid water could be very common inside comet nuclei at an early stage of their evolution. If we additionally consider the effects other potential sources of internal heating in the outer Solar system (Stern & Shull 1988), we come to the conclusion that it is very possible that comet nuclei may have left their outer Solar system reservoirs with a subsurface layer depleted in super volatile species in their pure condensate form.

However, the significant data set obtained on comets studied by spacecraft missions and summarized by Davidsson et al. (2016), appears to be consistent with comets not having suffered from any significant thermal processing during their time spent in either of the outer Solar system reservoirs. Alternatively, it is entirely possible that the effects of such processing, albeit only limited to subsurface layers, may have been erased by the subsequent evolution of comet nuclei on their way towards the inner Solar system. Indeed, sublimation of ices would cause the erosion of comet nuclei, the process which produces cometary comae, entrainment of dust sometimes in jet-like features, and chemical differentiation of the nucleus in the inner Solar system. If erosion is extremely limited beyond 3 au, where water ice (the main volatile constituent of nuclei) is stable, other more volatile species may sublimate. In addition, some other phase transitions like crystallization of amorphous water ice may occur in the outer Solar system, as evidenced for example by the existence of active Centaurs in the giant planets region. Centaurs are objects escaped from the transneptunian region, which lose mass and thus appear like comets. Water ice is thermo-physically stable on their current orbits, so their activity cannot be driven by its sublimation, although some more volatile species like CO may be involved. As of today, the source of the activity of Centaurs has not been definitively identified, and different processes may be involved for different individual objects (Prialnik et al. 1995; Capria et al. 2000; DeSanctis et al. 2000).

Nonetheless, if we consider that one single process must be responsible for the mass-loss of all active Centaurs, then the phase transition from amorphous and crystalline water ice may be able to fit the available data set (Jewitt 2009). Using a fully 3D model of heat conduction, Guilbert-Lepoutre (2012) investigated the occurrence of crystallization on Centaurs. They showed that crystallization is an ongoing process in the giant planet region, and can be considered as an efficient source of cometary activity, albeit limited to heliocentric distances up to 10–12 au, and to time-scales up to 10^4 to 10^5 yr. In their calculation, the crystallization front could propagate hundreds of metre deep in 10^6 yr, time-scale taken as a reference for the average lifetime of a Centaur on its orbit. In addition, crystallization could be triggered even at heliocentric distances as large as 16 au for objects having a high obliquity (>45°). Amorphous water ice was nonetheless able to survive at the surface of some cases studied, especially beyond 10 au. For their results, we can eventually come to the conclusion that the fact that some Centaurs are able to exhibit cometary activity is therefore a proof that processing to some degree is taking place for the overall population, so that short period comets, which incidentally should have travelled towards the inner Solar system through Centaur-like orbits, must have also suffered from the same processing.

2.2 Effects of a multistage injection into the inner Solar system

If the debatable effects of early heating are excluded, the long-term thermal history of a comet nucleus is determined by the heat flux transferred from its surface, due mainly to solar illumination, into its interior. Consequently, the coupled effects of orbital and thermal evolution need to be accounted for in order to estimate the amount of energy transferred to the interior of a nucleus throughout its journey in the Solar system, when trying to establish a relationship between the present state of a comet and its origin. In general, comets can be injected into the inner Solar system either on a direct path, or a multistage path. While long-period comets may preferentially follow direct paths, most short-period comet nuclei would leave their storage location to enter the inner Solar system by following chaotic orbits, owing to the gravitational perturbations of the four giant planets. Indeed, one major difference between short- and long-period comets is that the former can change orbits quite drastically on a time-scale of centuries, or even tens of years. Therefore, when considering the coupling between thermal and dynamical evolution, a complex multistage dynamical evolution may result in extensive changes of the internal composition and structure of comets, in marked contrast to the evolution resulting from a more direct injection.

The effects of a multistage injection into the Solar system have been summarized by Huebner et al. (2006), who performed a comparison between the final internal structure of a comet nucleus being injected via a direct and a multistage orbital process. They established the stratification of a fictitious comet nucleus resulting from each orbital stage of a multistage injection towards the inner Solar system, and compared the final stratification with the one resulting from a direct injection stage. For this comparison, they used a model of a comet with a dust to ice ratio of 1, an albedo of 5 per cent, a porosity of 80 per cent, and volatile abundance ratios to water of 1 per cent for CO_2 and 3 per cent for CO. In the multistage process, the outer layers of the nucleus were rapidly depleted in CO: when the comet arrived on an orbit with perihelion at 25 au, this super volatile species was sublimating from deep layers, so the activity was characterized by a continuous CO emission. Water and CO_2 did not follow this pattern, but were characterized by peak emissions towards the perihelion of each orbit. Thus, while CO was rapidly depleted from subsurface layers, other volatiles remained unaltered. Surface erosion only became significant for the simulated orbits where the perihelion distance was below 2 au. The simulations showed the formation of a transient dust mantle, which was destroyed when the last orbital changes occurred.

The 'final' orbit studied for this comparison was defined by $a = 2.664$ au, $e = 0.622$, resulting in $q = 0.999$ au. The similarities between the two orbital evolutions (direct and multistage) are: (1) surface temperatures, which is understandable given that the heat balance at the surface is dominated by free sublimation of water ice, the main volatile compound; (2) water and CO_2 emission fluxes, which are controlled by erosion which progressively ablate the surface, keeping both water and CO_2 close to the surface. The differences between the two orbital evolutions, which are significant differences indeed, are the locations of the CO and the amorphous/crystalline ice interfaces. In the multistage case, the CO interface ended up being located hundreds of metres below the surface, while it remained very close to the surface in the direct case, since the surface itself was being progressively eroded. CO emission from the 'multistage' nucleus was almost ten times lower than from the 'direct' one, and its emission pattern did not follow the water emission. The transition between amorphous and crystalline water ice behaved similarly to CO, the interface being located hundreds of metres below the surface. From the comparison we can draw the conclusion that supervolatile gases, if present in pure condensate, may be used as an indication of earlier evolution.

2.3 Concentric layering observed on 67p

Given the complex shape of 67P's nucleus, the stratification expected from long-term thermal processing may be defined by concentric layers with a geometry depending on complex irregular isotherms. Such layering is indeed observed on 67P, as evidence but different sets of complementary observations. From the analysis of VIRTIS observations, Filacchione et al. (2016) concluded that while the overall surface of 67P is coated with dark devolatilized material, exposed water ice shows a typical grain size which is consistent with grain growth by vapour diffusion in ice-rich layers or by sintering. Such stratification may result from the thermal processing affecting the uppermost layers of the nucleus while the comet orbits closer to perihelion. In addition, observations of the subsurface properties from MIRO and Philae instruments are consistent with the surface layer being more compacted than the rest of the interior (Ciarletti et al. 2015; Schloerb et al. 2015; Lethuillin et al. 2016). Therefore, sintering – the process that compacts porous material after heating – has thus been taking place in the past throughout the subsurface layer (Kossacki et al. 2015). Concurrently, volatiles have been depleted from 67P subsurface layers. This is best evidenced by the behaviour of CO_2 with respect to H_2O as observed by VIRTIS for example. Bockelee-Morvan et al. (2015) and Migliorini et al. (2016) both observed that the emission of H_2O does follow the local illumination conditions, being produced by detectable well-illuminated active areas, and being weakly emitted from areas of low solar illumination. This confirms that water ice is indeed present very close to the surface. However, CO_2 appears to be produced by both illuminated and non-illuminated areas of the nucleus, with a distribution that is more uniform. This is consistent with CO_2 sublimating from layers deeper than at least the diurnal skin depth (more volatile species would be sublimating from even deeper layers) after the subsurface layer has been depleted from such volatiles. One could argue that the observed stratification, being limited to the near-surface layers, has been produced in a recent past. However, this does confirm that the processes described in this section play an important role in the overall evolution of a comet nucleus, and 67P in particular. Furthermore, a larger scale stratification of the order of several hundreds of metres is also observed, as discussed in El-Maarry et al. (2015), Massironi et al. (2015) and Rickman et al. (2015). Massironi et al. (2015) deemed that this larger scale stratification should be primordial. Indeed, thermal processing alone cannot explain some critical aspects of the stratification observed on 67P: the sharp planar contacts across strata, the perpendicular orientation of the strata-planes relative to the gravity field of the two distinct lobes, or the lateral continuity of the related terraces. While thermal processing may concur in developing such features, they are probably the result of a combination of the two processes, primordial and thermally induced.

3 LATERAL CHEMICAL DIFFERENTIATION

The previous section described the radial processing of a comet, expected from the coupled orbital and thermal evolution of a nucleus from the outer Solar system reservoirs towards the inner Solar system. In this section, we want to emphasize that in addition to this radial layering expected from the thermal processing of bodies as they travel across the Solar system, some lateral differentiation may also occur, so we will focus on the study performed by Guilbert-Lepoutre & Jewitt (2011), who investigated the effect of a non-uniform albedo at the surface of a comet. Intuitively, we indeed expect that phase transitions like sublimation or amorphous water ice crystallization would proceed at different rates inside the nucleus if the energy balance varies over the surface of a comet. For example, on spherical objects the poles receive less energy than the equator (if the rotation axis is close to perpendicular to the comet orbital plane), so that at a given depth of the subsurface, the resulting composition may be different. Complex shapes, inducing shadows for example, but also varying thermo-physical properties such as albedo or thermal inertia are thus expected to produce a certain degree of lateral chemical differentiation.

3.1 Model

Guilbert-Lepoutre & Jewitt (2011) used a fully 3D model of heat transfer (Guilbert-Lepoutre et al. 2011) to constrain the extent of lateral differentiation which would result from non-uniform heating of the surface when comets are orbiting in the giant planet region, before their active comet phase. In this model, a comet nucleus is assumed to be a sphere, initially made of a porous mixture of ice and dust (with mass ratio of 1) uniformly distributed within the icy matrix. Water ice is initially amorphous, so that the phase transition between amorphous and crystalline water ice is investigated. The critical part in their modelling is the treatment of the surface, where the thermal balance is computed in each point of a 2D surface grid. Each point of this grid may hold a different set of thermo-physical properties than the others, which include:

(i) a different Bond albedo $\mathcal{A}$, which drives the effect of solar illumination described by $(1-\mathcal{A})\frac{S_\odot}{d_\mathrm{H}^2}\cos\xi$, with $S_\odot$ the solar constant, d_H the object's heliocentric distance, and $\xi \leq 90^\circ$ the local zenith angle,

(ii) the material emissivity ε, which drives the thermal emission $\varepsilon\sigma T_\mathrm{surf}^4$, with σ the Stefan-Boltzmann constant and T_surf the surface temperature,

(iii) the bulk density ρ_bulk, the thermal conductivity κ and the heat capacity c, which drive the lateral heat fluxes between different points of the surface, and the radial heat flux from and to the interior.

Guilbert-Lepoutre & Jewitt (2011) restricted their study to the effect of a non-uniform surface Bond albedo. They considered an overall surface with a 16 per cent albedo, well within the range of observed albedo of Centaurs (Lacerda et al. 2014), which correspond to the icy objects they studied. The surface is thus made of two components: a fresh ice/frost region with a 60 per cent albedo (1/8th of the overall surface) on an otherwise dirty ice or refractory surface with a 10 per cent albedo. We note that given that their equations are expanded on the basis of spherical harmonics, the model is limited to the investigation of spherical shapes.

3.2 Results

Guilbert-Lepoutre & Jewitt (2011) showed that non-uniform surface albedo induces varying thermal gradients in the subsurface layers, which can ultimately produce non-uniform composition. The emergence of such compositional non-uniformity was shown to depend on the difference in albedo between areas with low and high albedo, rather than on the value of the albedo itself. The thermal balance at the surface varied to the point that significant variations of phase

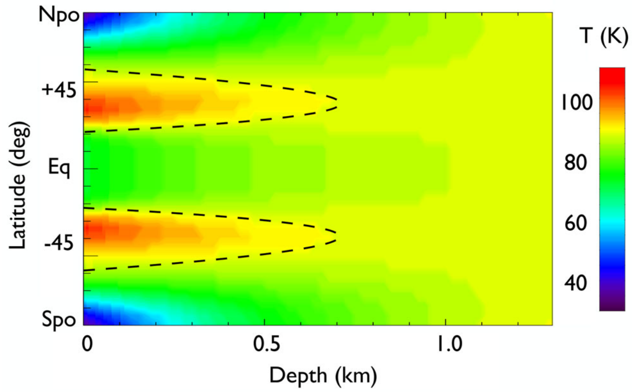

Figure 1. Temperature distributions along a meridian for a model with a surface albedo spot located between latitudes +22°.5 and −22°.5 (bottom panel), after 10 Myr on a Centaur orbit at 7 au as described in Guilbert-Lepoutre & Jewitt (2011). The boundary between amorphous and crystalline water ice is highlighted by a black dashed line.

transition rates were induced in the subsurface. When the crystallization threshold was locally reached, volatiles trapped in the amorphous ice would be released to migrate either towards the surface and out, or towards colder non-crystallized surrounding regions, where they could recondense. With time, these thermally shadowed regions could become strongly enriched in volatiles, while being surrounded by volatile-depleted material. The scale of the enriched regions would correlate with the size of the surface inhomogeneity that induced it.

The fully 3D description of gas molecule migration through a porous matrix is extremely difficult to achieve, and was not introduced in the study, where the gas phase was completely neglected. The effects of such a gas phase could strongly modify the results though, as it can locally affect thermo-physical properties such as the thermal conductivity or the porosity, and because the gas phase was identified in the KOSI experiments as a major medium of heat transport. In addition, instabilities caused by pressure build-up could develop, resulting in the disruption of some parts of surface layers. With this limitation in mind, Guilbert-Lepoutre & Jewitt (2011) predicted that the chemical lateral differentiation induced by surface inhomogeneities would nonetheless be long lived, since lateral heat fluxes remain very inefficient in erasing the subsurface structures. This is illustrated in Fig. 1, which shows that the non-uniform subsurface composition can be sustained over 10 Myr on the considered Centaur orbit. Consequently, we may expect that non-uniform compositions should be fairly common, so that compositional differences identified in a nucleus do not necessarily imply that a given comet was built from different cometesimals as described by Belton et al. (2007).

3.3 Lateral differentiation on 67P

In an attempt to constrain possible locations on 67P's surface where pristine material may be found, Kossacki (2016) showed that all locations on the surface are not processed to the same degree. While some locations are indeed able to preserve a pristine unconsolidated ice–dust mixture, other areas are subject to considerable modifications of both composition and structure. The thermal processing, which is studied by Kossacki (2016) on a limited time-scale, would therefore have significant consequences for the overall nucleus in terms of composition and structure. In addition, Keller et al. (2015)

showed that the energy balance at the surface can be extremely varied, especially when accounting for self-heating and shadowing. For example, the 67P's concave neck area receives 50 per cent more energy during the northern summer due to self-illumination. This emphasizes the importance of shape and surface heterogeneities in producing subsurface non-uniform compositions and structures. On a global scale, the dichotomy observed between the northern and the southern hemispheres of 67P is the result of heterogeneous heating. The south receives almost 10 times more energy and is thus more prone to erosion, so it is in a way more primitive, or shows less traces of past processing than the north. Both VIRTIS and ROSINA examinations of 67P's volatile content point to strong differences between the two hemispheres, which are consistent with different level of processing and different past evolution of the surface and subsurface layers on a global scale (Le Roy et al. 2015; Migliorini et al. 2016).

4 EFFECTS OF INTERNAL INHOMOGENEITIES ON THE ACTIVITY OF A COMET NUCLEUS

So far, we have shown how non-uniform insolation of a comet nucleus surface may induce not only a diversity in surface and subsurface properties, but also internal differentiation in terms of composition and structure. Subsurface inhomogeneities have been observed for example on comets 9P/Tempel 1 (Belton et al. 2013) and 67P (El-Maarry et al. 2015; Massironi et al. 2015; Vincent et al. 2015). The typical size of these inhomogeneities is similar to the size expected from the radial and lateral processing described in Sections 2 and 3. Whether produced by past thermal processing as described above, or primordial, as described by the *layered pile model* (consisting of a core overlain by randomly stacked layers differing in composition and physical properties, as the result of aggregation of smaller bodies, Belton et al. 2007), internal inhomogeneities have an effect on comet activity, which must be accounted for when interpreting the observed activity patterns of comet nuclei. In this section, we focus on the effect of primordial internal inhomogeneities, based on the studies of Rosenberg & Prialnik (2007, 2009, 2010), who developed a 3D comet evolution code that is suited for modelling inhomogeneous structures, involving asymmetric random distribution of internal properties.

4.1 Model

Similarly to the semi-analytical model described in Section 3, this model also adopts spherical geometry and uses spherical coordinates. The energy conservation equation in three dimensions is solved by a set of implicit difference equations, taking into account local heat sources, such as crystallization of amorphous ice, and local changes in composition and physical properties, such as thermal conductivity. The system of non-linear equations is linearized and solved iteratively. Boundary conditions at the surface consist of a balance of heat fluxes into the nucleus and out of it for each surface element. The numerical grid resolution does not allow modelling of small-scale effects on the surface, such as shadowing. Mass transfer is considered on the simplifying assumption of perfect permeability. Water ice may sublimate into the internal pores. As sublimation is expected to occur very close to the surface, vanishing pressure in the pores is assumed, meaning that the vapour escapes radially to the surface with no time delay. In this approximation, the vapour flux at each depth is given by the sum of vapour masses produced in the elements directly below it and the total production rate is simply obtained by the sum of the contributions of all surface elements.

An important feature of the calculation concerns dust production, which constitutes a major source of activity of any comet nucleus. Dust grains are dragged by the flow of sublimating gas and the process is modelled along with the gas production. Since the drag force depends on the grain size, grains of several different sizes are considered, distributed in mass over size bins, roughly equivalent to a power-law size distribution with a power of -3. At each grid point, the maximal size of grains that may be dragged by the gas is determined by comparing gravitational, centrifugal and drag forces acting on a spherical dust grain. Only grains that are smaller than both the maximal size and the local pore size will be dragged. As in the case of internally sublimated gas, dragged dust is transferred directly to the surface, and is added to surface dust production. The effect of mass loss on the local porosity is accounted for. The code also allows for local ablation, which may lead to the formation of mountains and depressions (Rosenberg & Prialnik 2010).

4.2 Results

Using the model briefly described above, Rosenberg & Prialnik (2010) studied the effect of internal inhomogeneities, introduced by piles or patches of material (*talps* as coined by Belton et al. 2007), which consisted of extended layers (about 9.5 per cent of the total nucleus surface), about 10 m thick, differing considerably from the ambient material in ice/dust ratios, densities and thermal conductivities. For instance, different ice/dust ratios and Hertz factors h (i.e. the correction of the thermal conductivity resulting from porosity) are used so to result in the different thermo-physical properties such as conductivity and density of various patches. While the homogeneous case is characterized by a mixture of 50 per cent dust and 50 per cent water ice in mass, the 'compact dust' patch is made of dust only with $h = 1$, and the 'fluffy ice' patch is made of 30 per cent dust, 70 per cent ice and $h = 0.01$. Several different types of such patches were assumed, so as to account for a wide range of possible aggregates.

First, individual patches were considered and the evolution of each comet model was followed through five revolutions around the sun in the orbit of 67P, so as to achieve a quasi-steady state, no longer affected by initial conditions. It was found that patches of different structure and composition affected the internal structure and dust mantle formation in different ways. Here, we show in Fig. 2 the effect of two types of patches, as well as a homogeneous case, for comparison. The advance of the crystallization front may be clearly seen in all the cases illustrated in Fig. 2. A sublimation front is seen closer to the surface. The outflowing gas drags with it dust particles, but since the larger particles are left behind, a dust mantle eventually forms. As its lower boundary advances inwards, an ice-depleted layer is produced, as shown in the panels. The depth of these layers and fronts at a given time depend on the presence and properties of patches, as illustrated. For example, we note that the dust mantle above the patch of compact dust is thinner than dust mantle of the reference, homogeneous model. A more significant difference is exhibited by the depth of the crystallization front: as the highly conductive compact dust patch draws heat from the ambient layer, crystallization slows down considerably as compared to the reference case. As another example, the poorly conductive porous ice patch causes a rise in the temperature above it, thus speeding the advance of the crystallization front. The dust mantle is slightly thicker above the porous ice patch, where the temperature is higher and sublimation stronger. In conclusion, pristine material is preserved closer to the surface above highly conductive material, and much deeper, when poorly conductive material is present.

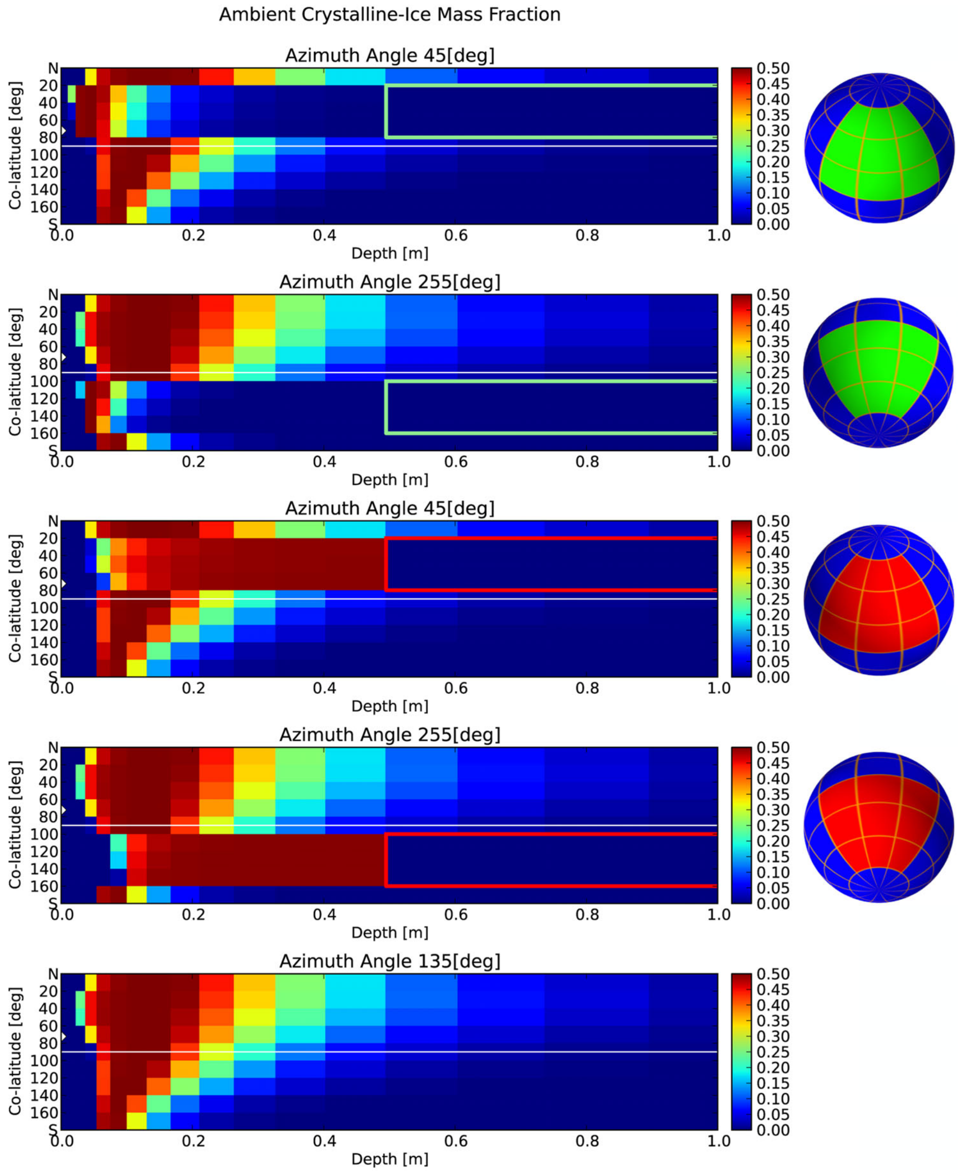

Figure 2. Mass fraction of crystalline ice as a function of depth down to 1 m (abscissa) and co-latitude (ordinate). Each panel – marked by its azimuth angle – represents a 'slice' of the nucleus. The bottom panel is used as the homogeneous reference case. The red and green frames mark the location of patches (red – porous ice, green – compact dust). The horizontal line represents the equator and the diamond marks the sub-solar co-latitude angle. The position of each patch is illustrated on the right-hand side of each panel.

The rate of ablation, too, is significantly affected by inhomogeneities, which may result in an uneven surface, as shown by Rosenberg & Prialnik (2010). Obviously, the overall ablation rate depends on latitude, but subsurface patches of different material add asymmetry to the pattern. For example, a compact dust patch cannot ablate and thus will remain as a mountain, while the surrounding material is ablated, while a porous ice patch, which sublimates faster, may create a depression, tens of metres deep.

Internal inhomogeneities may be detected in the activity of comet nuclei. As an example, Fig. 3 maps the H_2O production rate. Patches placed at different locations below the surface result in different production rate patterns over the surface, although the surface temperature map is the same. We have just shown that even one patch differing in structure and composition from the ambient material may lead to considerable variations in internal processing, as well as in surface properties and activity. Even more diverse activity patterns are exhibited by models of higher internal inhomogeneity, produced by many randomly distributed patches of various types. The opposite effects of highly conductive versus poorly conductive patches, when patches are randomly mixed, may create erratic behaviour. Thus, high production peaks, or outbursts may occur throughout the entire orbit, even close to aphelion. Short-duration outbursts near aphelion may exceed the perihelion peak production. For most of the outbursts, the ejected water vapour comes from the top ambient layer above a poorly conducting patch of porous ice. The low conductivity results in high internal temperatures (that may exceed the surface temperature), which in turn, lead to increased sublimation. In addition to affecting volatile production rates, the presence of internal inhomogeneities may affect local erosion, the progression of crystallization and the local thickness of dust mantles.

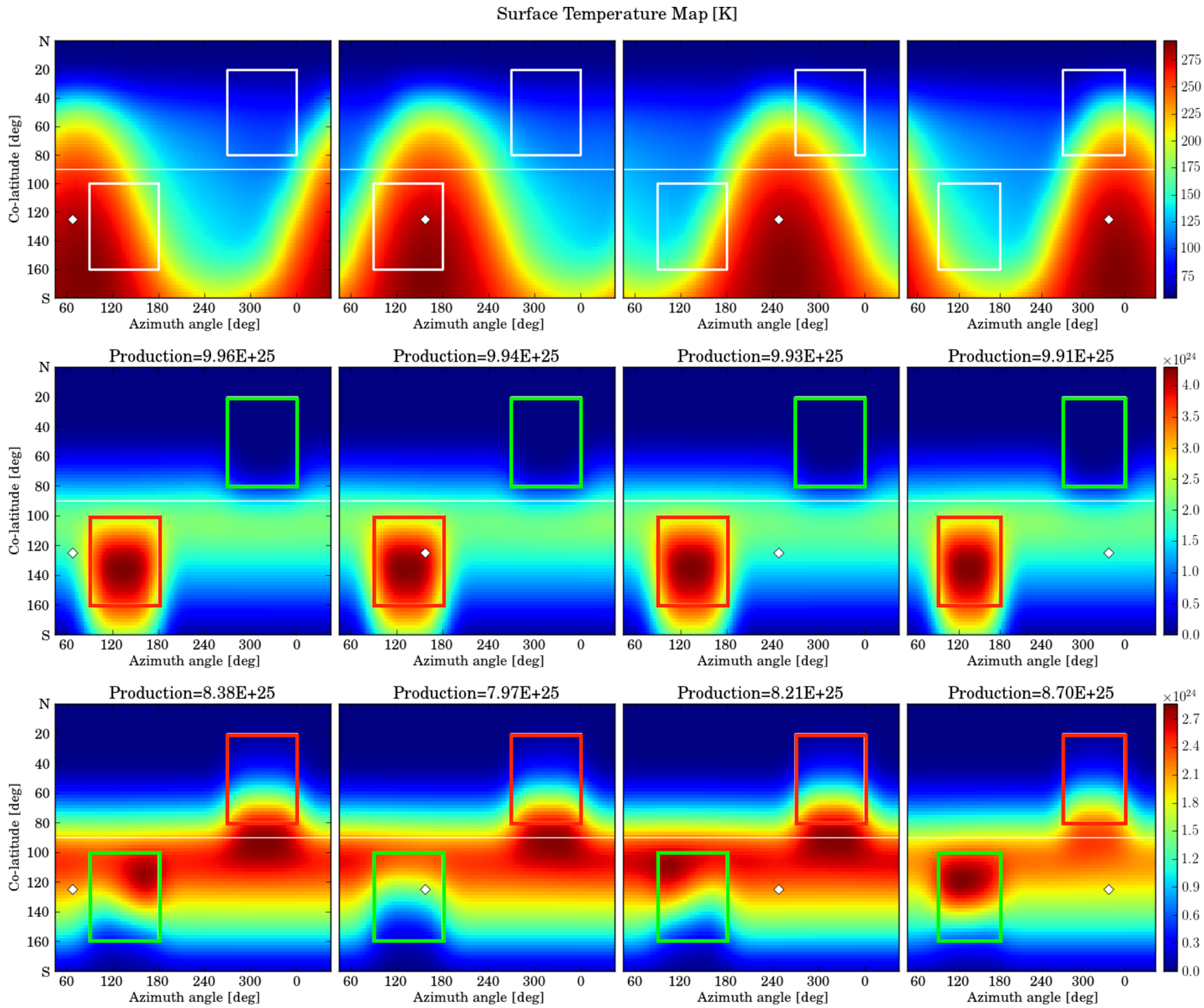

Figure 3. Temperature maps (top-row panels) and H_2O production maps (middle- and bottom-row panels) at 1.4 au pre-perihelion for a model in the orbit of comet 67P, where frames are taken at intervals of 1/4 of the spin period (about 3.2 h). The horizontal line represents the equator and the diamonds mark the sub-solar point. Top row: the surface temperature distribution is the same for any configuration of the patches, their position is marked with white squares. Middle row: green squares in the Northern hemisphere mark the position of the compact dust patch, red squares in the Southern hemisphere mark the location of the porous ice patch. Bottom row: patches are placed at the same locations, but interchanged (red for porous ice in the north, green for compact dust in the south). The total production rate is given at the top of each panel.

4.3 Effect of internal inhomogeneities on the activity of 67P

To summarize, the main effect of an initially inhomogeneous configuration (whether primordial or evolutionary), where patches are randomly distributed throughout the outer part of the nucleus, is a somewhat erratic activity, with peaks of water and dust production (outbursts) at all heliocentric distances. That cometary activity exhibits outbursts of diverse intensity and duration over a wide range of heliocentric distances has long been known. The results presented here suggest that such behaviour may simply arise from intrinsic internal inhomogeneities, without having to invoke special processes to explain it. Interestingly enough, the duration of these outbursts is typically of the order of days, similar to the outburst observed by the ESA/*Rosetta* OSIRIS camera at 4 au pre-perihelion on comet 67P (Tubiana et al. 2015). However, one should keep in mind that simplified models such as described here, are not meant to reproduce the behaviour of a given comet, but rather help understand the general behaviour patterns of comet nuclei and the diversity of surface structures in itself. Many arguments have however been put forward already to suggest that the nucleus of 67P is indeed heterogeneous. The observed outbursts may thus be the consequence of such heterogeneities.

5 PAST AND CURRENT PROCESSING OF COMET SUBSURFACE LAYERS AS REVEALED BY DEPRESSIONS ON THEIR SURFACE

5.1 Observations of circular depressions

Several comet nuclei have now been imaged by close-up spacecraft observations. These have revealed, in particular, that quasi-circular flat-floor depressions are present on the surface of these bodies, different from the structures expected for impact craters. These circular depressions were first observed by the Stardust mission on comet 81P/Wild 2 (Brownlee et al. 2004), then on comet 9P/Tempel 1 by the *Deep Impact* spacecraft (Belton et al. 2013), possibly on comet 103P/Hartley 2 by the *EPOXI* mission (Bruck Syal et al. 2013), and finally on 67P by the *Rosetta* mission (Vincent et al. 2015). The existence of these depressions offers the exciting prospect of constraining the physical and chemical processing of comets, so they naturally received substantial attention. In the first paper describing circular depressions on 67P, Vincent et al. (2015) suggested that their formation could be related to a sinkhole collapse mechanism. This would require either pre-existing cavities to be present in the near-surface layers of 67P, or that these cavities were created by the exothermic phase transition from amorphous to crystalline water ice, followed by the sublimation of local ices. Besse et al. (2015) suggested that a cycle may exist, between the formation, growing and destruction phases of these depressions, and that specific illumination conditions may be required for forming those structures.

Mousis et al. (2015) performed a detailed study of the three major phase transitions believed to occur on comets, in order to constrain the origin of circular depressions on 67P. They thus studied sublimation of ices, crystallization of amorphous water ice, and clathrate destabilization, assuming either a direct excavation process, or a formation of subsurface cavity followed by collapse. They used a 1D model of heat conduction, including gas diffusion, gas and dust release from the nucleus, dust mantle formation, surface erosion and the different latent heat exchanges due to phase transitions. The surface thermal inertia was assumed to be 100 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$. Each phase transition was studied individually. The depth of circular depressions observed on 67P is typically 200 m, so the processes were studied until they reached this characteristic size. Clathrate destabilization was shown to proceed in the shortest time-scale: the phase transition reached a depth of 20 to 30 m in 100 yr, and 200 m in about 800 yr. Crystallization of amorphous water ice was found to reach 200 m in about 2000 yr. Sublimation of water ice under the illumination conditions considered in their study (for the Seth region and the Seth_01 depression Vincent et al. 2015 in particular) was intimately connected to the formation of a dust mantle at the surface, which rapidly quenched any ice sublimation. Therefore, the process stopped rapidly. In order to overcome this problem, Mousis et al. (2015) had to assume that no dust was locally present, or that dust particles were very small in order to be efficiently dragged out with the gas, so not to form any dust mantle. The porosity of the dust mantle played an important role in determining whether the processes would involve a direct formation by excavation, or would form a subsurface cavity which could then collapse. Indeed, depending on the local porosity, phase transitions could be induced regularly if gas molecules were released easily, or episodically through eruptive processes if pores were sealed and pressure was allowed to build up below the surface. The authors therefore concluded that their results were consistent with both types of formation, either via sinkholes (Belton & Melosh 2009) or directly due to violent outbursts (Belton et al. 2013; Thomas et al. 2013). Ultimately, the process at the origin of the formation of circular depressions could not be identified though.

5.2 Revisiting the origin of circular depressions

Comet 67P has a chaotic orbit (Maquet 2015), and experienced several close encounters with Jupiter, the last two noticeable ones in 1959 and 1923 where the nucleus got closer than 1 au to the giant planet. The 1959 encounter modified the orbital elements of the comet quite drastically, since the perihelion distance changed

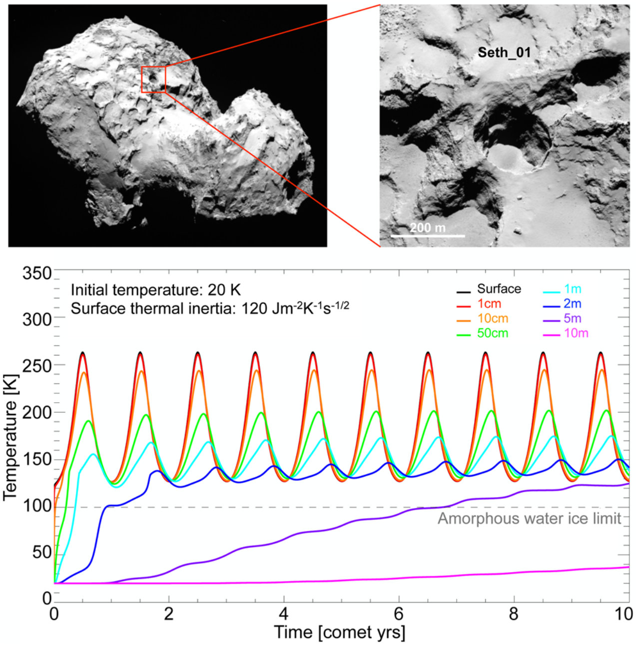

Figure 4. Bottom panel shows the evolution of the temperature at different depths for illumination conditions similar to those of the Seth_01 circular depression shown above. One comet year is 6.44 yr. Images from the OSIRIS narrow-angle camera, taken on 2014 August 3 for the comet, and on 2014 August 28 for the Seth_01 depression, credit ESA/*Rosetta*/MPS for OSIRIS Team MPS/UPD/LAM/IAA/INTA/UPM/DASP/IDA.

from more than 2.7 au to about 1.3 au. With this in mind, we wish to revisit the possible production of circular depressions on 67P, only limiting the time-scale for calculations to a maximum of 10 orbital revolutions, in order to examine the possibility for circular depressions to have been formed on 67P's current orbit. We used a fully 3D thermal model (Guilbert-Lepoutre et al. 2011) and studied the progression of the phase transition between amorphous and crystalline water ice. We used the same illumination conditions as Mousis et al. (2015) in order to make our results directly comparable to theirs. Thermo-physical parameters used in the model were also the same, except for the thermal inertia which we chose to let vary since the thermal inertia in pits regions is not firmly constrained and may vary between 10 and 150 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ (Leyrat et al. 2015). Fig. 4 shows the evolution of the temperature at different depths under a surface illuminated in the same conditions as in the case of the Seth_01 circular depression. The initial temperature in the calculations is 20 K, therefore the first orbit only shows how the material adjusts internally to the new heat balance. In the time 67P has spent in its current orbit, we find that the depth at which crystallization may proceed is less than 10 m.

If we consider a lower thermal inertia, it is even more difficult to bring enough heat at the required depth (100–200 m). This is best seen on Fig. 5, which provides a comparison between the evolution of the temperature distribution for a thermal inertia of 120 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$ and 40 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$. We conclude that the current illumination conditions observed in regions where pits are observed are not favourable to the formation of circular depressions of this typical scale, although metre-scale features could be created by crystallization of amorphous ice. Of course, erosion of the nucleus due to sublimation may be able to create the intricate, regular system of terraces, with many aligned terraces often in staircase patterns, described by Massironi et al. (2015), so

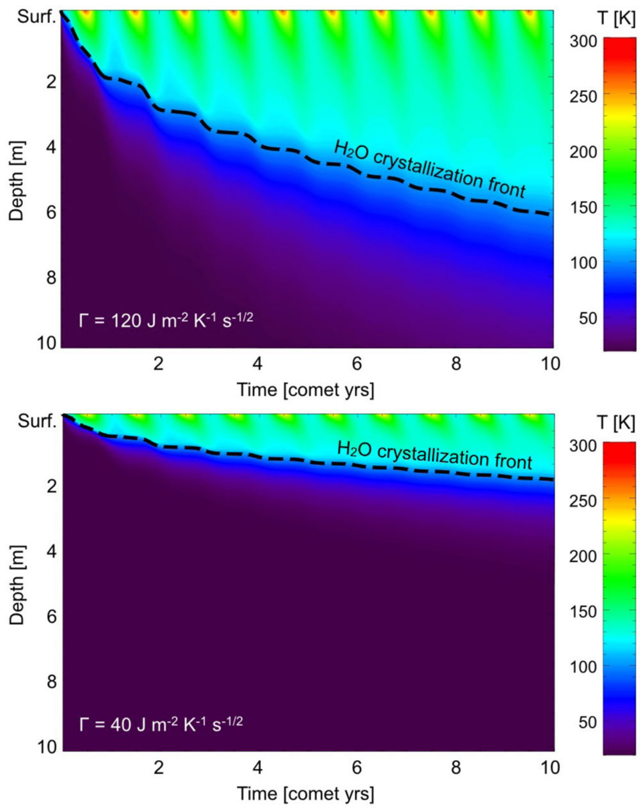

Figure 5. Temperature distribution as a function of time and depth under a surface illuminated similarly to the Seth_01 circular depression, for a thermal inertia of 120 $\mathrm{Jm^{-2}\,K^{-1}\,s^{-1/2}}$ (top panel), and 40 $\mathrm{Jm^{-2}\,K^{-1}\,s^{-1/2}}$ (bottom panel).

that growth of pre-existing or smaller depressions may be possible. However, the formation of local dust mantles may inhibit the regressive erosion process at some point, especially one the current orbit (Mousis et al. 2015).

Therefore, we concur with Ip et al. (2016), who studied these circular depressions from a morphological point of view. They showed that the size frequency distribution of the circular depressions has a similar power law distribution to those of 9P/Tempel 1 and 81P/Wild 2, which might imply that they were formed by the same process. However, we are still not able to point to the exact process at the origin of these features. Comparing the orbital history of those comets, they concluded that circular depressions may be dated back to the pre-JFC phase or the transneptunian phase of these comets. The asymmetry observed in the distribution of depressions on 67P might be linked to the primitive non-uniform structure of the comet, although it is more certainly due to the dichotomy in solar illumination. Indeed, the southern part of the comet is receiving almost an order of magnitude more energy than the northern part, and is thus more prone to erosion (Keller et al. 2015). We do not mean that circular depressions may not be formed, we mean here that they would have been erased. Only few depressions located on the edges of the Southern hemisphere would be expected to be observed. This is actually what is being observed on 67P as described in El-Maarry et al. (2016). In summary, it is very unlikely that circular depressions of the 100 m-scale were formed on 67P's current orbit, since it is extremely difficult to impossible to bring enough energy at the depths required for forming those structures. The mechanism for forming those features remains unconstrained up to now. In itself, the existence of circular depressions may be considered as a proof of the past processing of 67P's subsurface layers.

6 DISCUSSION

6.1 Features expected from past processing of comets in general

The studies we have reviewed in this paper hold a strong statistical significance when it comes to interpreting the current results of the ESA/*Rosetta* mission, even if those studies were not designed to be applied to 67P in the first place. For instance, dust to ice mass ratios or other characteristic of the comet nucleus itself, or of the material it is made of, may not be the ones currently observed by *Rosetta*. However, this is not a major problem. Indeed, using the current thermo-physical properties of 67P as initial parameters for studying its possible past processing would defeat the purpose of demonstrating that the physical processes responsible for such processing did actually shape the nucleus as observed today. Rather, the current thermo-physical parameters of 67P should be outputs of these models, and initial parameters should be derived by a trial and error procedure which would involve a significant and almost impossible work, given that the orbital evolution of 67P (hence the thermal processing linked to its orbital evolution) cannot be traced back accurately for more than hundreds of years. Therefore, we should here summarize the main outcomes of thermal models, which should be expected regardless of the accurate initial parameters used in such models.

While the inner part of a comet nucleus may remain unaltered by early evolution, its outer layers are expected to be processed, perhaps to a significant degree. Due to heating and subsequent phase transitions, an initially homogeneous comet nucleus may differentiate into a multilayer body, where only the deep layers can maintain their original composition and structure. The subsurface layers are depleted in various volatile species, with the surface layer being made of dust where the conditions are favorable. In a way, the outermost layers protect the deep ones, especially in the presence of a dust mantle, which is an efficient insulator. Thus, we expect the internal composition of comet nuclei to be stratified on the scale of hundreds of metres, with ices of increasingly volatile species at increasingly greater depths. This is especially true if the comet has been injected into the inner Solar system on a multistage path, which is most likely the case for JFCs that are prone to develop chaotic orbits owing to many close encounters within the giant planets region. In this case, the major differences with respect to direct injection indeed concern the final stratigraphy: CO and other supervolatile species would be expected to be depleted in the hundreds of metres of the outermost layers, and crystallization of amorphous water ice would be expected to proceed down to depths of hundreds of metres.

Similarly, the overall internal structure of comets is very likely non-uniform: density, porosity, or water ice phases are not only expected to vary with depth, but also laterally at a given depth. Non-uniform thermo-physical surface properties and shapes can generate long-lived thermal shadows in the immediate subsurface regions. Temperature-sensitive phase transitions proceed at different rates inside and outside thermal shadows, leading to the development of volatile-enhanced cold-traps. The resulting internal structures can be preserved on a time-scale of the order of 10 Myr or more, since lateral heat fluxes are very inefficient in erasing them.

6.2 Heterogeneous nucleus of 67P

Several lines of evidence, discussed throughout this paper, have been put forward to suggest that the nucleus of 67P is indeed inhomogeneous. Here, we want to emphasize again the work by Massironi et al. (2015), who analysed 67P's bilobate shape and the stratigraphy of its exposed subsurface to conclude that these two lobes are two different entities, and that each of them has an onion-like structure composed of many layers. The scale observed for the heterogeneities is conspicuously consistent with the one expected from the various thermal evolution models. While the overall surface layer of both lobes is thick ($\sim$650 m), the sub-layers have a typical thickness up to 100–200 m, and are inhomogeneous in composition. We wish to stress here that far from claiming that evolution produced such heterogeneity, we simply want to stress that the inevitable past processing of the nucleus cannot be overlooked when interpreting the complex results of observations provided by the ESA/*Rosetta* mission, especially since the properties of 67P's subsurface on a smaller scale are consistent with thermal processing playing an active part in shaping the current nucleus characteristics. Whether primordial or evolutionary induced, their existence does have effects on the actual activity of comets in general, and 67P in particular. They would affect water and other volatiles production rates, local erosion, the progression of crystallization, the dust mantle thickness. They would produce an uneven activity, characterized by a somewhat erratic behaviour, outbursts at any point of the orbit, even at a large heliocentric distance, activity on the night side, a differentiation of dust grain size in the surface layer, and an uneven surface by differential erosion, creating mountains, depressions and terraces.

6.3 Circular depressions: evidence for past processing of 67P?

Circular depressions have been observed at the surface of 67P (as they were observed on 81P, 9P and possibly 103P). They offer the exciting prospect of looking into the internal structure and the thermo-physical processing of comet nuclei. We find that it is very unlikely that 100–200 m depressions were formed on 67P's current orbit, since none of the known phase transitions is able to proceed sufficiently fast and deep to open a cavity that would then collapse, or to directly excavate the superficial layers. Therefore, the presence of circular depressions can be regarded as some evidence for the past processing of the nucleus. Since the results from the orbital evolution model indicate that the previous orbits would have been even less likely to produce these features (having perihelia distances further from the Sun than this current one), it may indeed be the case that circular depressions on 67P are the result of a long-term processing that still awaits to be understood. To summarize, we wish to stress in this paper the importance of thermal history, intrinsic inhomogeneities, as well as inhomogeneity resulting from thermo-physical processing, when trying to understand and interpret the results of observations of cometary activity.

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