Space Sci Rev (2015) 197:271–296
DOI 10.1007/s11214-015-0148-9

On the Evolution of Comets

A. Guilbert-Lepoutre[1,2] · S. Besse[1] · O. Mousis[3] · M. Ali-Dib[2] · S. Höfner[4,5] · D. Koschny[1] · P. Hager[6,7]

Received: 7 November 2014 / Accepted: 25 March 2015 / Published online: 15 April 2015

Abstract Studying comets is believed to bring invaluable clues on the formation and evolution of our planetary system. In comparison to planets, they have undergone much less alteration, and should have therefore retained a relatively pristine record of the conditions prevailing during the early phases of the solar system. However, comets might not be entirely pristine. As of today, we have not been able to determine which of the observed physical, chemical and orbital characteristics of comets, after they have evolved for more than 4 Gyr in a time-varying radiative and collisional environment, will provide the best clues to their origin. Comet physical characteristics as inherited from their formation stage may be very diverse, both in terms of composition and internal structure. The subsequent evolution of comet nuclei involves some possible processing from radiogenic heating, space weathering and large- and small-scale collisions, which might have modified their primordial structures and compositions with various degrees. When comets enter the inner solar system and become active, they start to lose mass at a very high rate. The effects of activity on comet nuclei involve a layering of the composition, a substantial non-even erosion and modification of their size and shape, and may eventually result in the death of comets. In this review, we present the dominating processes that might affect comet physical and chemical properties at different stages of their evolution. Although the evolutionary track may be specific to each comet, we can focus on long-lasting modifications which might be common to all

✉ A. Guilbert-Lepoutre
aurelie.guilbert-lepoutre@utinam.cnrs.fr

1 European Space Agency, ESTEC, 2200 AG Noordwijk, Netherlands

2 Institut UTINAM, UMR 6213–CNRS/Université de Franche Comté, 25000 Besancon, France

3 LAM, UMR 7326—CNRS/Université Aix Marseille, 13388, Marseille, France

4 Max-Planck-Institut für Sonnensystemforschung, 37077 Göttingen, Germany

5 Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, 38106 Braunschweig, Germany

6 Institute of Astronautics, Technische Universität München, 85748 Garching b. München, Germany

7 SpaceTech GmbH, 88090 Immenstaad, Germany

nuclei after their formation stage, during their storage in reservoirs in the outer solar system, and once comets enter the inner solar system and become active objects.

Keywords Comets · Evolution · Thermal processing · Collisions · Space weathering · Origins

1 Introduction

The solar system as we know it today displays a very complex architecture, in which three major reservoirs of small bodies can be identified. In the inner solar system, the Main Belt of Asteroids between the orbits of Mars and Jupiter was recently identified as a possible source of comets, as mass loss was observed for some of these objects. Although the source for such activity is not fully constrained yet (Jewitt 2012), the "Grand Tack" model, which examines the dynamical evolution of the solar system a few million years after the formation of the first solids (Walsh et al. 2011), suggests that some primitive icy objects formed beyond the giant planets could have populated this region. In the outer solar system, two main reservoirs can be identified: the transneptunian region holding two possible sources of comets, namely the Kuiper Belt and the Scattered Disk, and the Oort Cloud, an inferred structure at the edge of the solar system. Multiple models try to explain how the different dynamical features encountered in the outer solar system were formed, including the orbits of the giant planets or the complex dynamical structures in the transneptunian region. For instance, the Nice model addresses the dynamical evolution of the solar system after the formation of giant planets, and manages to reproduce many of these observed features (Gomes et al. 2005; Morbidelli et al. 2005; Tsiganis et al. 2005; Levison et al. 2008). However, it is still very difficult to explain the formation of all three sources of comets in the outer solar system in a consistent way (Charnoz and Morbidelli 2007). As of today, it is generally accepted that the Oort Cloud should be populated by objects formed in the 5–40 AU region, mostly in the 20–40 AU zone (Dones et al. 2004), that have been scattered out by the giant planets. The Scattered Disk should be populated by objects formed between 25 and 35 AU, which have been scattered mostly by Neptune (Duncan and Levison 1997; Morbidelli et al. 2004; Dones et al. 2004). Finally, the Kuiper Belt should contain objects mostly formed in situ ($\sim$30–50 AU) or moderately pushed during the chaotic dynamical evolution of the giant planets (Gomes 2003; Levison and Morbidelli 2003). Once stored in these reservoirs, comets can be perturbed by gravitational interactions and can be handed down through the giant planet region, toward the inner solar system. Jupiter Family Comets (JFCs) for instance are believed to come from the Scattered Disk (Levison and Duncan 1997; Tiscareno and Malhotra 2003; Gomes et al. 2008), while Long Period Comets (LPCs) and Halley-Type Comets (HTCs) could originate from the Oort Cloud (Dones et al. 2004) and the inner Oort Cloud (Levison et al. 2001) respectively.

Studying the composition of comets is believed to provide crucial clues on the physical and chemical processes which shaped the solar system. The composition of the protosolar nebula (PSN) and protoplanetary disk can be inferred from measurements of the Sun itself. Variations in composition, measured in comets for instance, can therefore be ascribed to physical or chemical processes which took place in the early stages of the solar system formation. Comets exhibit different physical and chemical characteristics (for example size, shape, or composition) as reviewed by Bockelée-Morvan et al., Cochran et al. and Lamy et al. in companion papers. While the range of sizes observed may be attributed to systematic differences among comet groups (Lamy et al. 2004), there may not be any compositional difference between JFCs and LPCs-HTCs (A'Hearn et al. 2012). However, within one dynamical group, comets might display a range of composition (A'Hearn et al. 2012), and nuclei with both uniform and non-uniform compositions have been observed (Dello Russo et al. 2007; Feaga et al. 2007; A'Hearn 2008). In order to link comets characteristics as observed today to their origin, we must try to distinguish whether the variety of physical and chemical characteristics is primordial or the product of evolutionary processes. The early physical evolution of comets, during the planet formation stage and before they reach their storage location either in the Oort Cloud or the Kuiper Belt, is a matter of strong debate. This evolution would be dominated by thermal processing and collisions, with a wide range of possible outcomes. During their 4.5 Gyr storage phase, comet surface layers would be altered mainly by space weathering, while interiors might have undergone modifications from residual radiogenic heating (if any), and thermal processing before they even enter the inner solar system.

Once a comet enters the inner solar system it evolves rapidly. The active-comet phase is dominated by the thermal processing of nuclei due to solar radiation, which has been studied by many authors (e.g. Huebner et al. (2006) and references therein). We gained a better understanding of the active-comet phase owing to great developments in laboratory experiments and numerical modeling, and few spacecraft missions. The first cometary mission, the ESA Giotto mission to 1P/Halley in 1986, has revealed a dark and porous nucleus, with active, less active, and completely inactive areas in its surface, the later being covered of non-volatile material quenching the ice sublimation (Keller et al. 1986). A few other comets were more recently studied by spacecraft missions, such as 19P/Borrelly by Deep Space 1 (Soderblom et al. 2002), 81P/Wild 2 by Stardust (Brownlee et al. 2004), 9P/Tempel 1 by Deep Impact (A'Hearn et al. 2005) and Stardust-Next (Veverka et al. 2013), and 103P/Hartley 2 by EPOXI (A'Hearn et al. 2011). Currently, the ESA Rosetta mission is orbiting comet 67P/Churyumov-Gerasimenko and is performing a detailed study never achieved before (see Sierks et al. 2015 or Thomas et al. 2015 for example). On a more general perspective, some comets can show a sporadic activity and sometimes outbursts, of which causes are not certain. Other comets show low levels of activity attributed to the progressive loss of near-surface volatiles. Eventually, some comet nuclei might become dead or dormant (see Jewitt 2004 for example), either from running out of volatiles or from catastrophic disruptions. In this paper, we present some long-lasting modifications of comets physical characteristics that would result from various processes, typically expected to affect the different stages of a comet's life.

2 Properties Inherited from the Formation Stage

2.1 Material Incorporated

2.1.1 Refractories

Cometary dust appears to be a mixture of silicate minerals, such as olivine and pyroxenes, both amorphous and crystalline (Hanner and Zolensky 2010), while a significant fraction of the carbon is expected to be in the form of organic refractory material. Such organic material was recently observed at the surface of 67P/Churyumov-Gerasimenko (Capaccioni et al. 2015). Minerals formed at high temperatures, including crystalline silicates that presumably condensed in the 1200–1400 K temperature range in the solar nebula (Hanner 1999), have been detected with ground-based telescopes in a large number of comets

(Campins and Ryan 1989; Crovisier et al. 2000; Sitko et al. 2004; Wooden et al. 2000, 2004, 2010). Cometary dust has been brought back to Earth from comet 81P/Wild 2 by the Stardust mission (Brownlee et al. 2006), which provided a direct way of studying refractory cometary material. The dust found in the Stardust samples consists of amorphous and crystalline silicates, metals and organics. All of these components been seen in primitive meteorites before, although never in the particular combination revealed by the Stardust samples. Possible aqueous alteration phases have been reported in the Stardust samples (Stodolna et al. 2012), although the most common products of aqueous alteration, phyllosilicates, have not been seen yet (Zolensky et al. 2006; Zolensky et al. 2008; Joswiak et al. 2012). The most intriguing result of the Stardust mission is the evidence of a large-scale transport of dust grains across the protoplanetary disk, given by the presence of minerals formed both in high and low temperature environments. For instance, the discovery of CAIs is puzzling because it is believed that CAIs were the first solids to form, close to the Sun during the earliest stages of the disk evolution (Grossman 1972; Jones et al. 2000; Simon et al. 2008). Therefore, the history of comet 81P/Wild 2, and by extrapolation of comets in general, must be more complex than previously envisioned.

A number of mechanisms has been proposed to explain the origin of these high-temperature minerals in comets. For example, the presence of shock waves triggered by gravitational instabilities in the outer PSN may anneal the amorphous silicates to crystallinity in situ prior to their incorporation in comets (Harker and Desch 2002). In these conditions, thermal annealing of submicron- and micron-sized silicate dust grains may occur in the formation region of comets, obviating the need for large-scale radial transport. However, the isotopic composition, minor element composition, and even the range of Fe/Si ratios measured in the dust that was returned by the Stardust spacecraft from Comet 81P/Wild 2 seem to rule out this scenario. There is indeed no model or experiment suggesting the possibility to form such compositions from plausible amorphous interstellar materials (Brownlee et al. 2006).

An alternative possibility is that small dust particles formed in the inner part of the PSN would have been redistributed outward during the dynamical evolution of the disk. In a classical model, the viscous stresses serve to drive mass inward with time and allow the disk to spread in the radial direction in order to preserve angular momentum (Shakura and Sunyaev 1973; Lynden-Bell and Pringle 1974). Hence, most of the disk gas moved inwards and was accreted by the protosun but some gas and gas-coupled particles would have been transported outwards. Because of its turbulent nature, gas follows random motions and leads to diffusion of material within it, allowing dust particles to be redistributed in a way that smooths out the concentration gradients (Ciesla 2009). Turbulence favors the rapid diffusion of the different gaseous compounds and gas-coupled solids throughout the nebula. One-dimensional (vertically averaged) diffusive transport of particles in the disk (Bockelée-Morvan et al. 2002), or two-dimensional transport through its surrounding layers (Ciesla 2007, 2009) and at various epochs of its evolution (Yang and Ciesla 2012) have therefore been proposed to account for the presence of hot temperature minerals in the formation zone of comets. It is uncertain however whether turbulent transport suffices to explain the observations, or whether alternative physical processes are also needed. Indeed, Hugues and Armitage (2010) investigated the outward transport of particles in the nebula via a combination of advection (inward drift of particles though interaction with gas) and turbulent diffusion in an evolving disk. These authors found that the advection of solids within the gas flow significantly reduces the outward transport efficiency for larger particles (typically a few millimeters), thereby limiting the extent of mixing uniformity that is achievable within the disk via turbulent diffusion.

Another proposed transport mechanism of dust within the solar nebula is photophoresis (Krauss and Wurm 2005; Wurm and Krauss 2006; Krauss et al. 2007; Mousis et al. 2007; Wurm et al. 2010; Moudens et al. 2011; Wurm et al. 2013). This effect is based on a radiation-induced temperature gradient on the surface of a particle and the subsequent non uniform interaction with surrounding gas. When the existence of an inner gap is assumed in the disk, this latter becomes optically thin enough for particles to see the protosun, but still has a reasonable gas content, which enables the photophoretic force to push dust grains outward (Mousis et al. 2007; Moudens et al. 2011). This process provides a mechanism to transport high-temperature material from the inner solar system to the regions in which the comets were forming. Eventually, the dust driven outward in this manner will reach a region where the gas pressure and irradiation are so low that the combined outward forces of radiation pressure and photophoresis can only balance the inward drift of particles, inducing the formation of a ring of dust at this location. So far, simulations of photophoretic transport require the presence of an inner gap in the protosolar nebula to enable the drift of particles towards the formation regions of comets (Moudens et al. 2011). Further studies will take into account models depicting the time evolution of the Sun's illumination from its earliest phases to present. Indeed, the assumption of an inner gap could possibly be avoided if one takes into account the increase of UV light from the early Sun.

2.1.2 Volatiles

Compared to refractories, volatiles condensed in form of ices are more sensitive to changes in temperature, whether in the protosolar nebula or later in comet nuclei, so that they offer a better diagnostic as to where comets might have formed. Therefore, understanding the composition of the gaseous and solid phase in the protoplanetary disk is a key step toward assessing the bulk composition of comets. Molecular hydrogen and helium gas contribute to most of the mass in the PSN. Refractories (material with high (>1000 K) sublimation temperatures) are thought to represent up to 0.6 % of the PSN (Asplund et al. 2009). Volatiles (molecular and atomic species with relatively low sublimation temperatures, in this context species like H_2O, CO, CO_2, NH_3 etc) may hold 1.4 % of the PSN mass (Lodders 2003; Asplund et al. 2009). Chemical-thermodynamic equilibrium calculations show that CO and N_2 may be the major C- and N-bearing species at temperatures higher than a few hundred K, and that CH_4 and NH_3 should dominate at lower temperatures (Cyr et al. 1999). However, non-equilibrium calculations indicate that the reaction producing CH_4 and NH_3 from CO and N_2 respectively is kinetically inhibited, so that CO and N_2 could have remained the dominant species at low temperatures (Lewis and Prinn 1980). This is supported by the observations of CO and/or CO_2 as being the main C-bearing volatiles in comets, as reported for example by the observations from the Deep Impact spacecraft of comets 9P/Tempel 1 and 103P/Hartley 2 and the AKARI satellite (Feaga et al. 2007; A'Hearn et al. 2011; Ootsubo et al. 2012).

Volatiles are supposed to be present in gaseous as well as solid form, depending on the temperature distribution across the protoplanetary disk. The distance at which a volatile specie can condense is referred to as the snowline. The locations of snowlines of molecules such as H_2O, CO or CO_2 should have dictated the bulk composition of comets. Determining the positions of such snowlines is key to probing the composition of planetesimals across the protoplanetary disk. The study of snowlines in the PSN is very uncertain (Pontoppidan et al. 2014), so that solar analogs are being used to perform this investigation (Qi et al. 2013). The H_2O snowline should be key to the formation of planetesimals in the Jupiter-Saturn region, whereas the CO snowline, estimated to be located at tens of AU from the

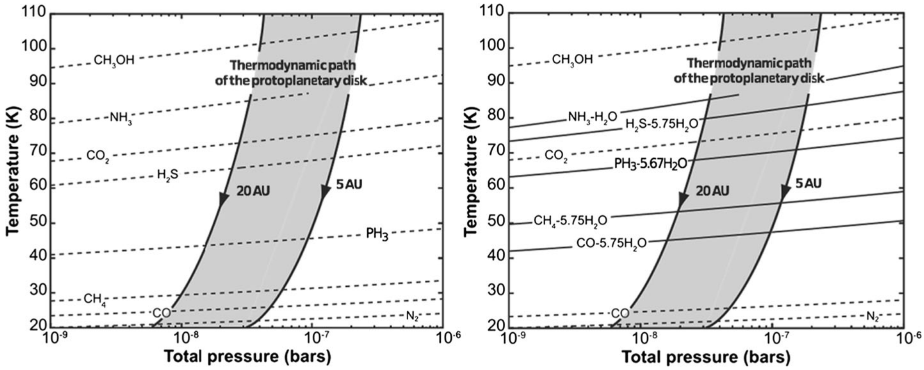

Fig. 1 Condensation sequence of the volatiles in the protosolar nebula. *Left*: Equilibrium curves of pure volatile condensates, along with the thermodynamic path of the nebula at 5 and 20 AU. *Right*: Equilibrium curves of hydrate (NH_3-H_2O), clathrates (X-5.75H_2O or X-5.67H_2O; *solid lines*), and pure condensates (*dotted lines*), and cooling curve of the solar nebula at 5 and 20 AU, assuming a full efficiency of clathration. Adapted from Madhusudhan et al. (2011)

protosun, should be key to the formation of planetesimals in the Uranus-Neptune region (Qi et al. 2013). However, the locations of snowlines may evolve with time. Indeed, in most classical one-dimensional and two-dimensional PSN models (Cassen 1994; D'Alessio et al. 1998; Hueso and Guillot 2005, for example), the disks midplanes cool down with time as their material essentially falls onto the parent star. This causes an inward migration of the snowline positions with time, as shown in Fig. 1. Recent layered-PSN models, including a midplane deadzone, predict more complex snowline evolutions (Martin and Livio 2012). Dodson-Robinson et al. (2009) suggests that between 3×10^4 yr and 10^6 yr, the CO snowline could have moved from 12 AU to 8 AU, while the H_2O line could have moved from 5 AU to 2 AU. Because comets exhibit a range of CO abundances, the CO snowline may have been located in the outer part of their formation region (Mumma and Charnley 2011). A'Hearn et al. (2012) suggests that the CO and CO_2 abundances could be explained if comets were formed between the CO_2 and CO snowlines. However, given the small number of comets investigated, there remains a possibility that the heterogeneity of volatile abundances among comets could be explained as a result of evolution in the inner solar system (Belton and Melosh 2009), or a combination of both formation and subsequent evolution.

In addition to their incorporation as pure condensates in the $\sim$20–30 K range in the PSN, volatiles may be trapped into the lattice of water ice grains. These icy grains may be formed from amorphous ice either condensed at low temperature ($<$70 K) in the outer layers of the protoplanetary disk (Ciesla 2014), or originating from interstellar medium where extremely low temperature conditions ($\sim$10 K) prevail (Gibb et al. 2004). We know from laboratory experiments that amorphous water ice has the ability to trap large amounts of volatiles, which can be expelled from the lattice upon crystallization (Bar-Nun et al. 1985, Owen and Bar-Nun 1998, Yokochi et al. 2012). The formation temperature range of amorphous ice appears consistent with the spin temperatures measured in H_2O and NH_3 in several comets and that cluster near 30 K (Mumma and Charnley 2011). On the other hand, volatiles can also be trapped in crystalline water ice in the form of clathrates during the cooling of the protosolar nebula. These clathrates have been hypothesized to contribute to the observed compositions of solar system bodies like icy moons of the giant planets (Lunine and Stevenson 1985; Mousis et al. 2010). Figure 1 shows the thermodynamic conditions needed for such trapping to occur. In this case, volatiles are trapped at temperatures higher than for amorphous water ice, and should also be released from the water ice matrix at higher temperatures than their respective sublimation temperatures.

While evidence from the study of refractories indicate a large scale mixing of dust grains within the protoplanetary disk, it is not clear yet whether such mixing occurred for icy grains. In particular, one key question is whether any large scale mixing of cometesimals (the building blocks of comets) may have taken place early in the evolution of the solar system. A'Hearn et al. (1995) argue that observational data are consistent with a mixing of water ice and other volatile species at the level of grains, rather than at the level of molecules, and that they appear to require the mixing of cometesimals of different compositions into individual comet nuclei. If so, this would indeed require that cometesimals were scattered among different regions of the PSN at the time comets were accreted. The extent of such scattering remains to be understood, since some nuclei might contain the full range of compositions observed within the whole population of comets (A'Hearn et al. 1995) and present a heterogeneous composition like 9P/Tempel 1 (Mumma et al. 2005; Feaga et al. 2007), while some other comets like 73P/Schwassmann-Wachmann 3 appear homogeneous on a macroscopic scale (Dello Russo et al. 2007; Kobayashi et al. 2007). However, for the volatile species studied by A'Hearn et al. (1995), the sample of observed comets seem quite uniform and only two main taxonomic classes may exist for the overall population: one typical class and a second depleted in C-bearing compounds.

2.2 Accretion and Collisions

There are currently two opposite views of the formation of comet nuclei: they could either be relatively unprocessed aggregates of cometesimals formed directly in the PSN, or collisional debris of larger bodies. A superposition of the two nuclei types might alternatively exist. In the later case (collisional debris), we need to consider comets along with Transneptunian Objects (TNOs) and Centaurs (all referred to as icy bodies), believed to be dynamically connected to JFCs (Levison and Duncan 1997; Tiscareno and Malhotra 2003). The largest TNOs, like Pluto, Haumea, Makemake or Eris, are defined as dwarf planets. JFCs on the other hand are smaller km-sized objects. There is therefore a wide range of icy bodies in the solar system, going from km to 10^3-km diameter objects. However, the size distribution of these objects is difficult to establish, since small objects are difficult to observe in the outer regions of the solar system, and large comets are lacking in the inner regions. Nonetheless, the size distribution of TNOs shows similarities with asteroids. Asteroids in the Main Belt have undergone some substantial dynamical depletion and collisional erosion. Using dynamical evolution models, we can link their current size distribution to their primordial birth size distribution. Weidenschilling (2011) suggests that a primordial population of 100 m bodies can reproduce the current asteroid population, including the knee at 100 km in their size distribution. However, Bottke et al. (2005) proposed that asteroids larger than 120 km should be primordial, and that the smaller objects should result from the collisional grinding of the larger ones. This is consistent with Morbidelli et al. (2009) who tested different formation models to determine that asteroids should have formed big. Similarly, the knee at 100 km in the TNO size distribution suggests that the typical cometesimal birth size should be about 100 km.

In addition, Stern and Weissman (2001) suggested that collisions between cometesimals in the giant-planet region would be catastrophic for most of the population, so that comet nuclei ejected into the Oort Cloud could mostly be collisional debris of larger objects. Stern (1995) and Davis and Farinella (1997) also argued that most JFCs are likely collisional fragments of disrupted parent bodies with initial sizes up to $\sim$100 km. However, recent calculations by Belton (2014) show that many comets would be primordial planetesimals relatively unaffected by impacts, rather than collisional debris of larger objects. The outcomes of such collisions on the physical characteristics of comets remain to be constrained. Comet nuclei visited by spacecrafts are lacking impact crater features that could help us identify physical and chemical characteristics linked to collisions (Soderblom et al. 2002; A'Hearn et al. 2011; Belton et al. 2013). However, the surface of these nuclei may have been refreshed due to subsequent cometary activity, and all traces of past collisions may have been removed (see for example Weissman et al. 2004). The observation of some bi-lobate shapes might indicate that smooth collisions could have produced the nuclei of comets 19P/Borrelly, 103P/Hartley 2 and 67P/Churyumov-Gerasimenko. Among the comets targeted by space missions, 9P/Tempel 1 and 67P/Churyumov-Gerasimenko display a layering in their composition (Veverka et al. 2013; Sierks et al. 2015), which could be the result some thermal processing (see following sections), or rather an argument in favor of early collisions during which a nucleus may accrete material of various composition (Belton et al. 2007a, 2007b). Although the predicted decrease in layer thickness is not observed on 67P, different sets of lineaments between its two lobes may indicate that these two parts may have been accreted by slow velocity collision at some point (Sierks et al. 2015).

Comet internal structures may help us understand the accretion process behind their formation. However, inferring this structure from the current available observations is challenging, although the results from the CONSERT experiment on Rosetta will provide the first determination of a comet's internal structure. Several models exist, that can explain many of the observed features of cometary nuclei and activity (see Weissman et al. 2004 and A'Hearn 2001 for a review). The current consensus may favor the rubble pile model (either primordial by Weissman (1986) or collisional by Weissman et al. (2004), and the Talps model (Belton et al. 2007a, 2007b). If so, the size of cometesimal incorporated into individual nuclei may be inferred, as reviewed by A'Hearn (2011). The layering observed on comet 9P/Tempel 1 by the Deep Impact mission does not appear like the pattern expected from most evolutionary models (A'Hearn et al. 2011) but rather like primordial cometesimals: Belton et al. (2007a, 2007b) inferred that these cometesimals should be $\sim$400-m objects. Some hints of the primordial size of cometesimals may also be inferred from splitting comets. Indeed, comets are known to fragment spontaneously with no obvious reason (see following section). The size of their fragments may tell us about the size of their constituting cometesimals (see Boehnhardt 2004 and Fernandez 2008 for reviews on splitting comets, and Knight et al. 2010 for a review on the size distribution of sun-grazing comets). These data are generally consistent with a typical size of cometesimals on the order of 50–100 m.

Once ejected into their storage regions, comet nuclei might not be significantly modified by collisions, in particular in the Oort Cloud which constitutes a dilute and cryogenic environment in which modifications of comets' physical and chemical properties are expected to be only limited. Indeed, collisions within the Oort Cloud, with an orbital speed of $\sim$0.2 km s^{-1}, have effectively no influence on the evolution of comets. Stern (1988) found however that impacts would be more significant in the Inner Oort Cloud (Duncan et al. 1987) so that comets stored in this region should have undergone some surface modification. Studies of the physical and dynamical evolution of comets suggest that collisions may play an important role in the Kuiper Belt (Stern 1995, 1996; Farinella and Davis 1996; Stern and Weissman 2001, Duncan et al. 2004).

2.3 Early Thermal Processing

It is not clear whether impact-induced or accretional heating would have actually played a significant role in the global evolution of comet compositions in this early stage of their life. The thermal effect of collisions on comets is poorly known, although it might potentially be inferred from what we know of the collisional processing of asteroids. We therefore consider it useful to review the thermal consequences of impacts among asteroids, for which many studies have been performed. Impacts have been invoked to explain the metamorphism and melting seen in meteorites, especially when such events occurred lately (>5 Myr after CAI formation) in the history of meteorite parent bodies, when short-lived radioactive nuclides had already decayed (Rubin 2004; Schulz et al. 2012 and references therein). However, impacts would have been unable to drive a global-scale thermal processing of asteroids, since impact heating remains localized and can only affect a small volume of the target body. Keil et al. (1997) suggested that the global temperature increase after impact would be approximately 10 K. Davison et al. (2010) studied the influence of porosity on impact heating, and showed that collisions on porous objects would result in higher temperatures than on non-porous objects. However, they estimated that the globally-averaged temperature increase would also be of the order of 10K. Considering the speed of collisions in comet forming regions, the temperature increase would be expected to be quite small too (see Huebner et al. 2006).

Comets are however made of volatile species, more sensitive to variations of the temperature, so that small increases of the temperature can be relevant for the evolution of the composition of subsurface layers. Laboratory experiments show for example that collisions under present day dynamical conditions would result in the melting of water ice at the point of impact (Stewart and Ahrens 2004). The production of craters filled with melts that subsequently rapidly solidified as glass have been observed in the lab (Koschny et al. 2001; Love et al. 1993). In addition, Ciesla et al. (2013) showed that the post-impact structure of asteroids would be strongly influenced by their pre-impact internal structure, in particular with respect to the layered structure resulting from radiogenic heating. They found that heating would be mostly localized around the point of impact, and that radiogenically-heated internal material, which would have remained buried under the surface for a non-impacted object, would flow to the surface. This process would lead to an overall increased cooling rate of the impacted asteroid, implying that collisions on targets affected by radiogenic heating would help cooling them instead of further heating them. Therefore, if comets were formed big like asteroids, they could have been affected by an impact-induced thermal processing in the early stages of their physical evolution, yet to be constrained, in addition to the thermal processing described below.

The decay of ^{26}Al has long been recognized as a potentially powerful heat source, capable of melting rocky body interiors. Its actual effect on the thermal evolution of comets remains to be fully constrained though. In particular, whether this nuclide was actually accreted in comet nuclei however remains debatable. The study of meteorites and Stardust samples should be helpful in understanding the early evolution of comets. The dynamics of meteorite delivery to the Earth are well understood (Morbidelli and Gladman 1998; Vokrouhlicky and Farinella 2000), and all meteorites for which a precise orbit has been calculated originate from the asteroid belt (Gounelle et al. 2006 and references therein). There is thus a large consensus that asteroids are the source of all meteorites, except for a few which are lunar or martian meteorites. To understand if comets can produce meteorites worth studying in the laboratory, we should understand whether comets can impact the Earth. Gounelle et al. (2008) estimated that impacts of JFCs on Earth should be very

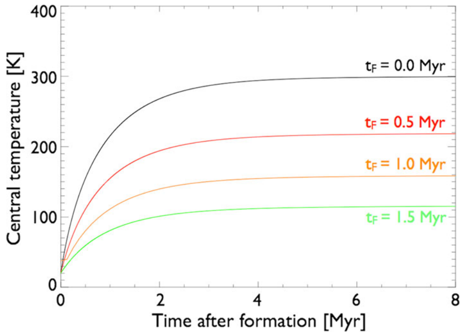

Fig. 2 Evolution of the central temperature for a 30 km comet parent body, with realistic physical characteristics (density of 700 $kg\,m^{-3}$, thermal conductivity of 10^{-2} $Wm^{-1}\,K^{-1}$), under the influence of radiogenic heating due to the decay of short-lived radioactive nuclides. The different lines correspond to different formation times after CAI formation: the longer the formation time, the smaller the amount of decaying radioactive nuclides available for heating comet interiors. Based on Mousis et al. (2012)

rare, and—given the very short lifetime of small comets in the inner solar system—could be considered as non-existent in practice. Despite the intense modeling effort, the impact rate of comets versus asteroids with Earth is still not constrained (see Gounelle et al. 2008, for a review). Although pathways from the outer solar system should be extremely rare, they can exist. In fact, Gounelle et al. (2006) suggested that the orbit of the Orgueil meteorite could be more compatible with that of a JFC, than with that of an asteroid. Impact probabilities with the Earth and entry velocities suggest that the proportion of cometary meteorites compared to asteroidal meteorites should be small but not zero. The study of Stardust samples shows that they contain minerals that were all previously seen in primitive meteorites, though the combination found in comet 81P/Wild 2 could not be matched to any known meteorite type. Although Ca–Al rich Inclusions (CAIs, believed to be the first solids to condensate in the solar system) were detected in the Stardust samples, the measurements of the decay product of short-lived radionuclide ^{26}Al, ^{26}Mg, do not show the former presence of ^{26}Al.

The $^{26}Al/^{27}Al$ ratio, with a canonical value of 5×10^{-5} (MacPherson et al. 1995), appears consistent in CAIs and meteorites of different classes which argues for a uniform distribution of ^{26}Al within the solar system (Huss et al. 2001). CAIs with low ratio ($\sim 5 \times 10^{-6}$) have been reported (Kunihiro et al. 2004; Makide et al. 2009), so that the existence of such inclusions, or the inclusions with no radiogenic excess of ^{26}Mg found in the Stardust samples, is perceived as a reason to invoke a non-uniform distribution of ^{26}Al within the solar system (Makide et al. 2011; Krot et al. 2012; Ogliore et al. 2012). This constitutes the first impediment to our understanding of the early thermal processing of comets. The second impediment comes from our lack of knowledge of the comet formation process itself, both in term of size (see previous section) and timescale (see Fig. 2). Indeed, given its short lifetime, the effectiveness of ^{26}Al in heating a comet interior strongly depends on the nucleus formation time with respect to the CAIs formation. Prialnik et al. (1987) found that with an initial $^{26}Al/^{27}Al$ ratio of 5×10^{-5}, the heat released upon decay would have resulted in the complete crystallization of amorphous ice, and even melting of comet cores for objects larger than 6 km. Haruyama et al. (1993) showed that comet thermal histories are very sensitive to thermal conductivity, leading to very high temperatures and full crystallization of the comet interiors, or alternatively very limited temperatures not higher than 100 K. According to Prialnik and Podolak (1995), the early thermal evolution of comets could have lead to distinct configurations, depending on their size, thermal conductivity and formation time.

Table 1 Estimated irradiation dose in eV/16-amu molecule for 4.6 Gyr, with an ice density of 1.0 g/cm^3, from Hudson et al. (2008)

Distance from the Sun (AU)	At 1-µm depth	At 100-µm depth	At 1-m depth
5–35 (Giant planet region)	100–10,000	100–200	30
40–$\sim$1,000 (Transneptunian region)	100–500,000	100–30,000	30–50
$\sim$40,000–100,000 (Oort Cloud)	500,000	30,000	50

A pristine structure could be thoroughly preserved, or the interior could be partly to completely crystallized except for a negligible outer layer which might remain primitive. The occurrence of high internal temperatures and production of liquid water would be strengthened when accounting for the effect of accretional heating, affecting the early evolution of comets concurrently with radiogenic heating during the short lifetime of ^{26}Al. Merk and Prialnik (2006) showed that the occurrence of liquid water in 2 to 32-km radius bodies may be a very common phenomenon. For example, they find that for a given set of initial parameters, all accreting objects with a final radius above 4 km could produce liquid water cores, extending from 10 to 90 % of the overall interior.

3 Processing During the Storage Phase

3.1 Effect of Space Weathering

Stern (2003) argued that even during the quiescent storage phase of comet nuclei, some evolutionary processes like thermal processes or radiation might play a role. Space weathering describes processes affecting the surface of airless bodies, such as bombardment by micrometeorites, irradiation by UV photons, solar wind particles and cosmic ray ions. A particle passing through an ice layer looses its energy by producing secondary particles, which in turn lead to many excitations in the surface material. These events result in the breakage of molecule chemical bonds, and the rearrangement of molecule fragments to produce new complex molecules. From laboratory experiments (Brunetto et al. 2006; Brunetto and Roush 2008; Hudson et al. 2008; Modica et al. 2012), we know that the simple molecules found in comets and their parent bodies, such as CH_4 and CH_3OH, are easily destroyed by space weathering, so to produce more complex organic molecules leading to the formation of a crust of refractory material. Indeed, such an organic-rich surface has recently been observed for comet 67P/Churuymov-Gerasimenko (Capaccioni et al. 2015). After prolonged irradiation, this crust might evolve into a layer of amorphous carbon (Strazzulla and Baratta 1992). Irradiation of cometary surfaces by high energy particles and photons is therefore a dominant evolutionary process during the storage phase of comet's life, whether in the Oort Cloud or the Kuiper Belt, as shown by the study of the radiation distribution in the outer solar system, performed both by theoretical modeling and in situ spacecraft measurements (see Hudson et al. 2008 for a review and Table 1).

Space weathering has a number of effects relevant in understanding the evolution of comets since it can cause significant variations in the surface properties such as color, composition, or other physical and optical characteristics. The progressive destruction of

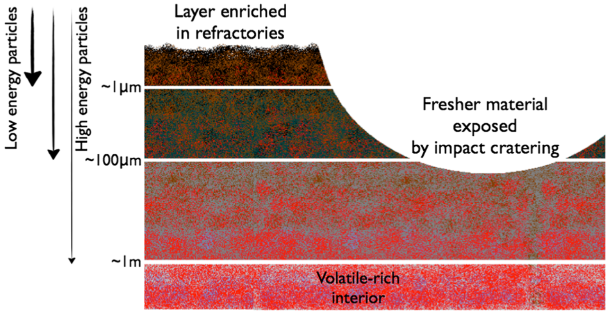

Fig. 3 Schematic illustrating the effects of irradiation by high energy particles on subsurface layer of icy objects in the outer solar system, and the effect of localized impact cratering. Based on Guilbert et al. (2009)

molecules leads to their signatures being progressively erased from comet spectra. Additionally, laboratory studies have shown that initially bright and flat spectra evolve into redder and darker spectra with increasing irradiation dose (Brunetto et al. 2006 for example). These characteristics are typically observed among comets, since they usually display a very low albedos (see Lamy et al. 2004), and red visual spectral slopes. As an example, we may mention the recent results of Capaccioni et al. (2015) who measured an albedo of 6 % and a visual slope of 5 to 25 %/100 nm for comet 67P/Churyumov-Gerasimenko. However, there is a superposition of reddening and darkening that needs to be accounted for, since initially red spectra can evolve into flat dark spectra (Kanuchova et al. 2012). Ultimately, in the presence of organics, space weathering trends are not well established yet. The end-result chemistry depends on whether the ice is initially pure, or if several ices are mixed together, i.e. on the initial composition of the mixture present at the surface of comet nuclei. In addition, irradiation by energetic particles can induce sputtering of surface molecules. This process is especially important for icy satellites, exposed to energetic ions trapped into the magnetosphere of giant planets. However, sputtering can also occur on cometary surfaces, due to irradiation by energetic solar wind ions. Among the potential effects of sputtering, we can expect some changes in composition, depletion in volatiles, erosion of the surface, variations of the surface texture, albedo and porosity (Palumbo 2006; Dartois et al. 2013). In particular, sputtering is believed to participate to the formation of comet mantles in the Oort Cloud (see Johnson 1995 for a review).

In summary, space weathering leads to the formation of an irradiation layer on the upper few meters of a comet nucleus. This mantle is expected to be carbon-rich and depleted in volatiles i.e. chemically transformed compared to the initial composition of cometary surfaces. From laboratory experiments, Strazzulla et al. (1991) suggested that in the Oort cloud the external 0.1 to 0.5 m thick layer of comet nuclei would be exposed to an irradiation dose sufficient to produce a substantial nonvolatile layer. Local removal of this layer due to impact cratering (illustrated by Fig. 3) could induce variations in the overall observed color, albedo and composition of the surface, and lead to very complex inhomogeneous surface properties, occurring before the comets enter the inner solar system. This external layer could survive the subsequent sublimation of underlying ices (Strazzulla et al. 1991; Strazzulla and Palumbo 2001). However, it is generally assumed that irradiation layers would be blown off or be buried by subsequent outgassing, and would not survive a comet first entry in the inner solar system.

3.2 Thermal Processing

The thermal processing of comets during their storage phase is usually assumed to be limited, since the equilibrium temperature in the outer solar system reservoirs is very low. However, when it comes to the survival of supervolatile species like CO or N_2, all potential heating needs to be accounted for. The processing of comet nuclei by radiogenic heating, as described previously, is relevant here since some residual ^{26}Al might still be decaying at the time comets enter their storage phase, either in the Oort Cloud or the transneptunian region. Long-lived isotopes like ^{40}K, ^{235}U, ^{238}U or ^{232}Th would inevitably decay over the age of the solar system, generating a possible more moderate but more extended heating of TNO interiors, and therefore play a significant role in differentiating the largest parent bodies. Between 30 and 50 AU, radiogenic heat can in fact be comparable to solar radiation. However, the actual outcome of radiogenic heating, both in the Oort Cloud and in the Kuiper Belt, depends on the amount of radiogenic elements accreted in comets and on the physical parameters, such as thermal conductivity, porosity, or the size of the nucleus. Thermal evolution modeling performed for porous comet nuclei with $R > 10$ km shows that these objects may have completely preserved their initial stratigraphy, or have completely crystallized (assuming they were initially composed of amorphous water ice), or developed a 'differentiated' structure, with a crystallized core, a layer of condensed volatiles, and pristine outer layers made of unaltered material (Prialnik and Podolak 1995). In addition to this radiogenic heating, Stern and Shull (1988) proposed that up to 20 % Oort cloud comets could have been heated to at least 30 K to a depth of several dozen meters, due to the passage of luminous stars. They suggested that most of them might have been heated as high as 45 K to a depth of 1 m from stochastic supernovae events. This would lead to the formation of a surface layer where super volatiles would be absent in their pure condensate form (they could have survived as molecules trapped in water ice). Stern (2003) summarized that passing stars and supernovae heating events may mask the primordial composition of comet nuclei down to 5 to 50 m for stars, and 0.1 to 2 m for supernovae.

After leaving their storage location, comet nuclei may enter the inner solar system following chaotic orbits, owing to the gravitational perturbations of the four giant planets. They can be injected into the inner solar system either on a direct path or a multistage path, sometimes extremely hard to track back from their current observed orbit. We consider here the effect of thermal processing before comets perform their first passage close to the Sun. We stress that the multistage process is not efficient in injecting comets into the inner solar system, since a minority of comet nuclei are found to reach short-period orbits without being ejected of the solar system (Everhart 1969). If we consider the coupling between thermal and dynamical evolution, a complex multistage dynamical evolution may have resulted in a complex and drastic modification of comets internal composition and structure, different from the ones resulting from a more direct injection. While a direct-injection orbit would most likely lead to volatile-depleted layers protecting internal ones, thereby preserving the pristine composition, multistage-injection orbits can be such that surface layers are strongly ablated and the underlying pristine material exposed. Huebner et al. (2006) performed a comparison between the "final" stratigraphy of a comet nucleus being injected via a direct and a multistage process. In the multistage-injection nucleus, the CO interface is located at a depth of more than a hundred meters, while it remains close to the surface for the direct-injection nucleus. Similarly, the interface between amorphous and crystalline water ice (assuming water ice is initially amorphous) is found more than a hundred meters below the surface in the multistage-injection nucleus, but remains close to the surface in the direct-injection nucleus. They also found that the subsequent CO emission from the multistage-injection nucleus would be almost ten times less than from the direct-injection one, and that its pattern would not follow the water emission. From the comparison, they conclude that the behavior of volatile gases could be used as a diagnostic for earlier evolution. A sudden outburst of volatile gases can indeed be a diagnostic of a recent orbital change, as suggested in the case of 46P/Wirtanen (Jorda and Rickman 1995).

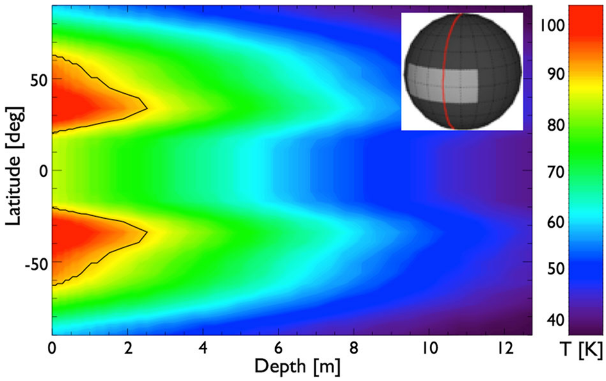

Fig. 4 Temperature distribution across a meridian cut of a comet subsurface layer. The surface holds a patch of higher albedo, casting a long-lived thermal shadow in the subsurface. *Black solid line* gives the location of the crystallization front. Adapted from Guilbert-Lepoutre and Jewitt (2011)

In addition to the radial layering described above, Guilbert-Lepoutre and Jewitt (2011) suggested that a lateral chemical differentiation would be expected from comet nuclei with non-uniform surface properties. They studied the evolution of the internal composition of comet nuclei orbiting on Centaur-like orbits, following the idea that a dynamical cascade between Kuiper Belt objects, Centaurs and Jupiter Family Comets might exist (Levison and Duncan 1997; Tiscareno and Malhotra 2003). They found that surface inhomogeneities, due to local variations of the albedo for example, would cast long-lived thermal shadows in subsurface layers. This would result in strong lateral modifications of the composition at a given depth, with regions in the thermal shadows being enriched in volatiles and surrounded by crystallized and volatile-depleted material (see Fig. 4). The superposition of the two processes, radial layering and lateral chemical differentiation, could therefore lead to some very complex internal structures, possibly mimicking the structures inherited from a complex formation mechanism such as described in the Talps model (Belton et al. 2007a, 2007b), before comets even entered the inner solar system. Recent collisions could also produce some localized variations of physical properties such as composition, color, albedo, porosity or thermal inertia, which would in turn increase the importance of thermal shadowing described before. Koschny et al. (2001) and Burchell et al. (2002) suggested that dense impactors may end up embedded into the surface of their targets, leading to possible strongly inhomogeneous surfaces. For instance, in an extreme case, a volatile-free projectile might get trapped into a volatile-rich cometary surface. In addition, Housen et al. (1999) and Housen and Holsapple (2003) suggested that collisions would result in the local compaction of the surface material, rather than in the traditional crater excavation flow, leading to strong variations of the thermal conductivity across comet surfaces. We stress again that observations of comets from spacecrafts have revealed that nuclei are lacking impact crater features that could help us identify physical and chemical characteristics linked to collisions, although craters would likely be removed by erosion due to subsequent cometary activity on a short timescale, and not expected to be observed (Weissman et al. 2004).

4 Active-Comet Phase

4.1 Loss of Volatiles

The active phase has been studied by many authors. We refer to extensive reviews by Prialnik et al. (2004) or Huebner et al. (2006) for detailed discussions on this intense period of a comet's life during which changes are expected to occur on its shape, size, or rotation properties (Jewitt 2004). Several mechanisms, like sublimation, clathrate devolatilization or crystallization of amorphous ice, can be identified to explain the mass loss observed during the active-comet phase. Sublimation of ices is the primary driver for cometary activity in the inner solar system. While volatile species like CO or CO_2 would start to be released at large heliocentric distances, depending on their sublimation temperature, water ice sublimation becomes important inside $\sim$3 AU (Meech and Svoren 2004). Clathrates devolatilize at specific temperatures, lower than the sublimation temperature of water ice. Once a clathrate has devolatilized, water ice remains crystalline until it reaches its own sublimation temperature. In addition, if amorphous water ice is present, its transition to crystalline water ice may be initiated. In this case, all volatiles released upon crystallization would escape the comet nucleus together, independently of their sublimation temperature. However, these mobilized volatile molecules can diffuse toward colder regions inside the nucleus where they can refreeze. Whether amorphous water ice can be preserved inside comets is a matter of debate, since it has never been observed directly. There could be some indirect evidence that amorphous water ice might have been able to survive close to the surface of comets though. For instance, the phase transition between amorphous and crystalline water ice has been invoked to explain the activity at large heliocentric distance of Centaurs (Jewitt 2009; Guilbert-Lepoutre 2012) and comets beyond 5 AU (Cochran et al. 1992). The phase transition is also one of the processes considered to explain cometary outbursts. For example, crystallization of amorphous ice, accompanied by the release of occluded volatiles and dust was invoked to interpret the outbursts observed for 1P/Halley (Espinasse et al. 1991; Prialnik and Bar-Nun 1992), C/1995 O1 (Hale-Bopp) (Prialnik 1999, 2002, Capria et al. 2002), and more recently 17P/Holmes (Hillman and Prialnik 2012). Therefore, coma observations alone are insufficient in constraining the composition of comets, since the abundances of volatiles in the nucleus are not mirrored directly by the observed abundances in the coma (Huebner and Benkhoff 1999).

The fraction of solar radiation that is not reflected or used for the different phase transitions at the surface of comets may be conducted into the nucleus (see Fig. 5). The depth reached by this process depends many unknown or poorly-constrained thermophysical properties such as porosity, pore size distribution, inertia or local geomorphological features. If the heat wave reaches volatile-rich layers, the same phase transitions may occur. We note that below the thermal skin depth (determined by the surface thermal inertia), the material is not sensitive to day-night variations of the surface temperature. Volatiles mobilized from subsurface layers could flow outward or diffuse inward through a complex network of pores where they would eventually refreeze (Benkhoff and Boice 1996). Since transition rates are strongly temperature dependent and vary from one volatile specie to an other, several distinct sublimation and condensation fronts and are expected to develop inside the nucleus. This process also leads to a chemical differentiation of the subsurface layers, with near-surface layers being depleted in volatiles over a few orbital periods, and the formation of a stratified structure (Prialnik et al. 2008; DeSanctis et al. 2007). We note however that the evidence from the Deep Impact mission to 9P/Tempel 1 suggest that the layering observed does not appear like the stratified structure expected from most thermal evolution models (A'Hearn 2001). They also suggest that the internal composition, as inferred from the few meters of subsurface layer studied, is not strongly differentiated, or that the differentiation expected from solar radiation processing proceeded below 20 m. The case of 9P/Tempel 1 may illustrate the fact that surface erosion and chemical differentiation are in competition, so that surfaces may erode as rapidly as differentiation fronts proceed into the nucleus. In addition, Jewitt (2004) argues that given

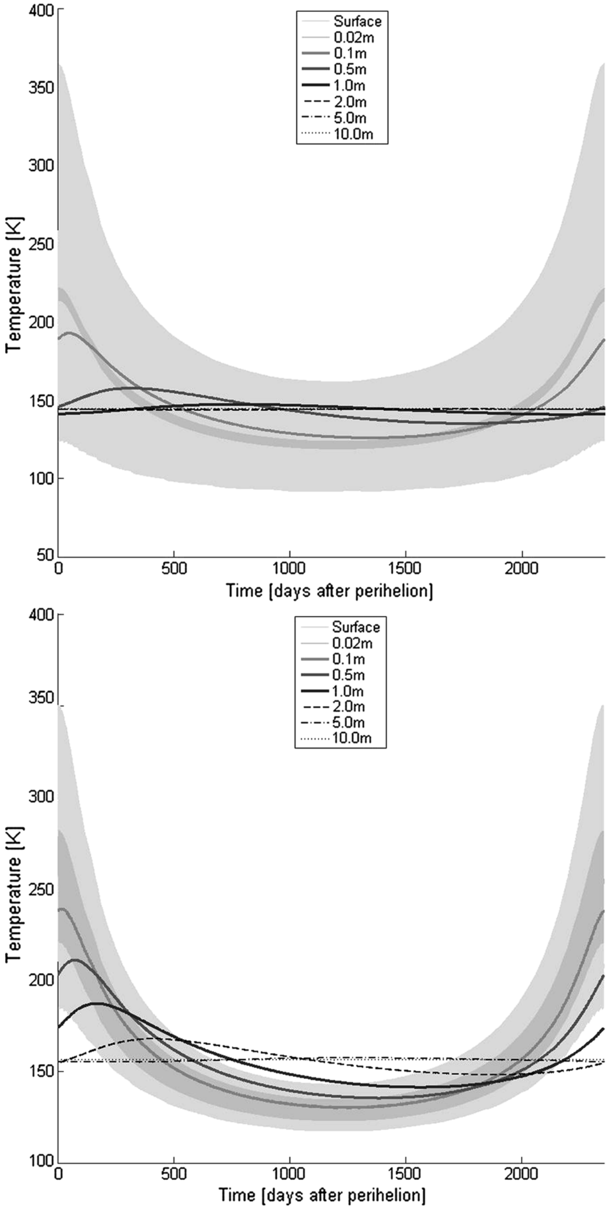

Fig. 5 Evolution of the temperature at selected depths and for different porosities over one orbital period of a Jupiter Family Comet (semi major axis of 3.5 AU and eccentricity of 0.64). Upper layers are affected by day-night variations of the temperature (*grey areas*), while below the skin depth the material is not sensitive to such variations. A higher surface porosity (*upper image*, thermal inertia of 20 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$) is linked to a lower conductivity, and results in a shallower penetration of the heat wave. Less porous material (lower image, thermal inertia of 100 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$), with higher conductivity, allows a deeper propagation of the heat wave. The effect of sublimation is not considered here, so to keep the problem simple. Sublimation would delay the propagation of the heat wave to deeper layers, as it consumes a significant fraction of the transported energy

the typical heat-conduction timescale for comets, deep interiors (below 1 km) should be thermally decoupled from surfaces. This process is complicated by the presence of dust, and the unknown internal structure, primordial and inherited from the evolutionary track followed before comet nuclei entered the inner solar system. Indeed, Rosenberg and Prialnik (2010) showed that internal inhomogeneities would affect the activity pattern of a comet and possibly produce outbursts at large heliocentric distance.

When solar radiation is dominant, orbital properties such as the spin rate or the inclination of the spin axis start to play an important role in the evolution of comets. They trigger a non-uniform heating of cometary surfaces which, combined with a low thermal inertia and an initially specific compositional structure, can result in strong modifications of local thermo-physical properties as well as uneven erosion, and in strong changes in the nucleus shape (Cohen et al. 2003). This shape would lead to distinct illumination functions for various areas at the surface of a comet, with some regions being almost permanently shadowed. In about a hundred orbits, the variable sublimation rate would lead to changes in the moment of inertia and spin properties, thus repeating the cycle of thermo-physical, compositional and structural changes. As summarized by Jewitt (2004), the various side effects of activity, such as changes in shape, size or rotation period are all closely intertwined. Space missions have revealed that comet nuclei have active, less active and completely inactive areas on their surface. Areas with higher material strength can become dead zones with respect to sublimation (Blum et al. 2014), so would areas covered by a layer of dust quenching ice sublimation (see following section). Ground-based and spacecraft observations have identified dust jets in the inner coma of many comets, which could be linked to confined areas on the nucleus (e.g. Keller et al. 1988; Belton 2010). Observational data suggest that active and non-active areas may be distinguished not only by illumination conditions, but also by topography and composition. It is not clear yet whether the geomorphological features observed at the surface of comets visited by spacecrafts are the result of past uneven outgassing, or the cause for such localized activity. For example, two types of terrains have been observed at the surface of 9P/Tempel 1 and 103P/Hartley 2: pitted terrains with a rough appearance, and smooth terrain where erosion and deposition took place (Thomas et al. 2013a, 2013b; Bruck-Syal et al. 2013). A scarp of higher albedo was observed, and interpreted as being due to some activity-driven surface reshaping (Farnham et al. 2013).

4.2 Dust Surface-Layer Formation and Death of Comets

The problem of dust layer formation has been studied since Brin and Mendis (1979). The existence of the mantle of dust at the surface of comets has been inferred from ground-based observations (Jewitt 1992, A'Hearn et al. 1995), and confirmed by recent space mission observations (see Gulkis et al. 2015; Thomas et al. 2015). When ice on a comet nucleus sublimates, it lifts dust grains previously embedded within the ice matrix, leaving at the surface those too heavy relative to their effective cross section to escape the nucleus weak gravitational field. Although initially large dust particles are isolated from each other, the surface gets covered with dust as particles accumulate. The gas flow through such a mantle can be modeled by considering gas diffusion through the porous medium. Jewitt (2002) estimated that a dust mantle would grow in $\sim 10^3$ years at 5 AU and 1 year at 1 AU. If the gas pressure is high enough, the dust layer may be blown off and the process will start again. Kuehrt and Keller (1994) suggested that eventually, the pore size of this dust mantle would be too small to allow particles to escape, leading to a very stable mantle, with a cohesive strength larger than the vapor pressure of sublimating ice underneath. When the mantle becomes thicker than the diurnal thermal skin depth, it seals the interior so that cometary activity would be quenched, as observed in the KOSI experiments (Grün et al. 1993). Any gas would be driven toward the interior, thus forming an ice layer of increased density (Spohn et al. 1989; Prialnik and Mekler 1991). Skorov and Blum (2012) reassessed the problem of dust mantle formation in the light of recent spacecraft observations showing ice sublimation coming from underneath a dry hot cohesive dust layer, and dust emission being correlated with gas activity (e.g. A'Hearn et al. 2011), and water ice being found ~ 1 m below a volatile-poor surface layer (A'Hearn et al. 2008). They studied the formation and removal of a dust layer at the surface of comets by evaluating its tensile strength. They showed that the sublimation of water ice would not be able to remove the dust mantle, while the sublimation of CO would, within a repetitive cycle of dust mantle formation and destruction, since gas pressure below the crust increases as the crust thickness increases. This seems to be in agreement with the results from the EPOXI mission toward 103P/Hartley 2, where water vapor was observed to come from the dust-covered region in the neck (A'Hearn et al. 2011).

Meteoroid observations are relevant to the study of dust mantle properties, since the bulk of the meteoroid population originates from comets, being blown away from the nucleus as ices sublimate close to the Sun. For instance, 1P/Halley is associated with the Aquarids and Orionids, and comets 21P/Giacobini-Zinner and 109P/Swift-Tuttle with the Draconids and Perseids respectively. Some meteoroids can also come from asteroids: 3200 Phaeton is indeed believed to be the parent body of the Geminids (thermal fracture has been invoked to explain the mass loss of Phaeton, Jewitt and Li 2010). How much information we can gain on comets and cometary activity from a meteoroid stream remains to be understood, since detailed orbital analysis of dust particles ejected from comets started only recently (e.g. Brown and Jones 1998; McNaught and Asher 1999; Lyytinen and Van Flandern 2000; Vaubaillon et al. 2005). The light curve and magnitude of a meteoroid can be used to assess dust properties such as density or strength. For instance, the Draconids contain extremely friable meteoroids with a very low density (Ceplecha 1968). More generally, the cometary material observed in meteoroids exhibits a low strength, of less than 1 kPa, the strength of fresh snow (Borovicka et al. 2007). In situ measurements performed from the Deep Impact spacecraft yielded an extremely low value ($<$65 Pa, A'Hearn et al. 2005) although any strength between 0 and 12 kPa has been shown to fit the observations (Holsapple and Housen 2007). More generally, the estimation of comet tensile strengths leads to low values, as expected for very porous bodies (Davidsson 2001; Toth and Lisse 2006). The study of the tidal breakup of comet D/1993 F2 (Shoemaker-Levy 9) led to an extremely low value of the tensile strength (Greenberg et al. 1995; Asphaug and Benz 1996). These low values are in agreement with laboratory measurements of the tensile strength of loosely packed micron-sized dust particles (Blum and Schrapler 2004; Blum et al. 2006).

Therefore, once a comet is injected into the inner solar system, it progressively decays. The median dynamical lifetime of a JFC is of the order of 10^5 years (Levison and Duncan 1994), although they follow a chaotic trajectory among planets, so that they retain a dynamical memory of only $\sim$1000 years (Tancredi 1995). A comet is considered active when it is producing a detectable coma, and inactive when the coma is not detectable, generally in the outer part of its orbit due to low insolation at large heliocentric distance. A comet is considered dead or dormant when no detectable coma can be observed at any point of its orbit: this was for example the case of comet 107P/Wilson-Harrington which was lost in 1942, and rediscovered as an asteroid-like object finally named (4015) Wilson-Harrington. Following the aforementioned description of the dust layer formation, one obvious reason for becoming a dead, or rather dormant, is the lack of volatiles available near the surface, due to previous cometary activity (comets would become dead when all volatiles would be consumed). The timescale for thermal devolatilization is of the order of $10^5 \times r$ years, with r the nucleus size in km (Jewitt 2004). This is comparable to the dynamical timescale for JFCs of km-sized objects, so that it is reasonable to expect that some comets might become dead or dormant, in the sense that they might have lost all or part of their initial volatile content respectively. Many comets display a very low level of activity, which is usually interpreted as a sign of their progressive loss of volatiles in the subsurface layers (Luu and Jewitt 1992). In addition, following the idea of a dynamical cascade between Scattered Disk Objects beyond

Neptune and JFCs, Belton (2014) suggested that in order to reproduce the size distribution of TNOs as constrained by recent surveys (Fuentes et al. 2010; Schlichting et al. 2012; Zhang et al. 2013), the current population of JFCs must contain a large fraction of defunct comets.

If comets can die from running out of volatiles, other mechanisms such as splitting can strongly limit their lifetime. A compilation of data on splitting comets by Weissman (1980) and Boehnhardt (2004) suggests that splitting would statistically occur of 10 % of Oort Cloud comets, 4 % of long-period comets and 1 % of short-period comets. Levison et al. (2002) also showed that 99 % of Oort Cloud comets would disaggregate on their first passage in the inner solar system. These numbers might reflect different internal properties, either primordial or evolutionary. Comets might be disrupted by tidal interaction with the Sun or a giant planet. The best example could be comet D/1993 F2 (Shoemaker-Levy 9), which was tidally disrupted by a close encounter with Jupiter in 1994, or the parent body that gave birth to the Kreutz group of sungrazing comets (Marsden 1989; Knight et al. 2010). Other comets may disrupt with no obvious reason, like D/1999 S4 which fragmented as it passed through perihelion in 2000 (Weaver et al. 2001). Boehnhardt (2004) suggested that over a lifetime as a comet, a nucleus might loose a mass equivalent to a 500 to 1000 m radius body, i.e. the typical size of a JFC. Therefore splitting and fragmenting should be an important process to be accounted for in the evolution of comets. In absence of tidal interaction, the mechanism behind the fracture of splitting comets is still unknown. Several other mechanisms can explain the splitting of comets, such as rotational spin-up (Weissman and Lowry 2003), gas pressure release (Samarasinha 1999). However, when the event is associated with a burst of activity, the process may be connected to internal stresses or pressure build-up. Indeed, if gas is being accumulated inside the nucleus more rapidly than it can be removed by flowing through porous ice or dust on the surface, large stresses may be experiences by the cometary subsurface material. If the pressure is not released rapidly enough to prevent an instability, this mechanism could lead to a major outburst, such as the one recently observed for comet 17P/Holmes. This comet experienced the largest outburst event in recorded history (Moreno et al. 2008; Li et al. 2011), during which the nucleus lost $\sim$5 % of its mass at most (Reach et al. 2010). Similarly, comet 73P/Schwassmann-Wachmann 3 shed fragments twice in past recorded history, but is still returning as an active comet, hence not disrupted. In the worst cases, comet nuclei could be completely disrupted by such an event. The temporal gap between the outburst and the splitting observed in many non-tidally split comets was interpreted as being due to the sustained activity that is required to fracture the material (Sekanina et al. 2002). If true, this constitutes a strong argument against the idea that comets should be strengthless rubble-pile objects. Other splitting mechanisms include internal frictions due to changes in the moment of inertia caused by uneven outgassing, resulting in a nucleus fragmenting at its weakest structural parts.

5 Discussion

We study comets because we believe that they hold invaluable clues on the formation and evolution of our planetary system. In comparison to planets, they have undergone much less alteration, having been exposed to fewer evolutionary processes that acted preferentially at their surface. Therefore, they should have retained a relatively pristine record of the conditions prevailing during the early phases of the solar system. Interpreting this record via observations, laboratory experiments and numerical modeling can thus tell us a lot about how our planetary system formed. However, we still have not been able to determine which of the observed physical, chemical and orbital characteristics of comets will provide the best clues to their origin, after they have evolved for more than 4 Gyr in a time-varying radiative and collisional environment. We have exposed the major processes that dominate the processing of comets at different stages of their evolution. Ultimately, we need to emphasize that the evolutionary track may be specific to each comet. Comet physical characteristics as inherited from their formation stage may be very diverse. Nuclei could be formed of a single component, either relatively uniform in composition, or heterogeneous if comets accreted material from different regions when migrating through the protoplanetary disk. Alternatively, comet nuclei may be made of multiple components loosely bound together. These sub-units may similarly be relatively uniform, or could originate from different regions of the protoplanetary disk. So far, direct observations by spacecraft missions have revealed that both types of nuclei, single- or multiple-components, exist. Furthermore, some of the observed nuclei might be collisional debris of larger, possibly chemically differentiated parent bodies. The subsequent evolution of comet nuclei involves some processing from radiogenic heating, space weathering and large- and small-scale collisions, which modified their primordial structures and compositions with various degrees. When comets enter the inner solar system and become active, they start to loose mass at a very high rate. The effects of activity on comet nuclei involve a layering of the composition, a substantial non-even erosion and modification of their size and shape, and may eventually result in the death of comets.

Because evolutionary processes may lead to so many different outcomes, we need to focus on their long-lasting effects. The initial population of icy bodies in the early solar system might have included a significant number of objects with sufficient thermal processing to alter their original composition. Depending mainly on the formation time of comets, but also on initial parameters such as internal structure, composition, porosity, or thermal conductivity, the outcomes of the early evolution of comets due to thermal processes could be very diverse. Pristine structures could have been preserved, but physical and chemical differentiation could have occurred, leading to unknown modifications of comets initial thermophysical properties. The current presence of highly volatile species like CO and N_2 seems to argue against a full scale modification of the original chemical composition, but rather tends toward limited alteration. The decay of radioactive nuclides could have nonetheless lead to the depletion of volatiles from the innermost layers of comet nuclei. Even if no liquid phase was produced, cometary material is such a poor heat conductor that residual heat from ^{26}Al or long-lived nuclides might have lead to the formation of volatile-depleted cores. If the population of icy objects was dominated by large cometesimals, so that current comet nuclei would mostly result from the collisional grinding of larger objects, then these parent bodies should have formed slowly and/or late with respect to CAI formation so to decrease the amount of ^{26}Al available to heat them, or they should have formed in a ^{26}Al poor environment. Comets could have also formed small, although the wide spectrum of alteration results described before is applicable even for km-sized objects. The study of meteorites is not clearly helpful in constraining the possible early thermal processing of comets yet. Although the Stardust samples do contain some CAIs, the lack of former ^{26}Al seems to argue against any strong early processing due to radiogenic heating. However, the samples do show hints of aqueous alteration, but lack the most commonly formed minerals. This suggests that (i) 81P/Wild 2 did not suffer from significant internal heating, (ii) the aqueous alteration minerals were debris from a different parent-body, then re-accreted at a later stage in this comet, or (iii) these minerals were formed locally for example in impact sites. In turn, this suggests that 81P/Wild 2 was presumably formed small and/or late with respect to CAI formation, but it is difficult to extrapolate this conclusion to the overall comet population, and argues in favor of sample-return spacecraft mission toward a comet.

As of today, little is known of the actual role of collisions in the evolution of comets, since impact craters have never been undoubtedly observed at the surface of comets visited by spacecrafts: pits seen on the surface of 81P/Wild 2 (Brownlee et al. 2004), 9P/Tempel 1 (Belton et al. 2013) and very recently 67P/Churyumov-Gerasimenko (Sierks et al. 2014) could be interpreted as impact craters (Basilevsky and Keller 2007), but could also be caused by outbursting activity (Belton 2010). Possible reasons include: (i) these comets were never impacted, (ii) impact cratering was not efficient, as suggested by experiments adding species more volatile than water (Burchell et al. 1998; Burchell and Johnson 2005), or (iii) the inevitable subsequent erosion due to cometary activity removed craters and other impact-related features from their surface. There are however supporting evidence for recent collisions among populations dynamically related to comets. In the Kuiper Belt, we know of one dynamical family which was produced by impact (the Haumea family, Brown et al. 2007). In the giant planet region, a ring system was recently detected around Centaur (10199) Chariklo (Braga-Ribas et al. 2014), which was interpreted as the result of a recent collision (Duffard et al. 2014). In summary, thermal processing during the early and late stages of comet evolution, and collisional processing lead to the superposition of two types of chemical differentiation, both radial (layering) and lateral. They are therefore expected to lead to some very complex internal structures, possibly mimicking the structures inherited from a complex formation mechanism such as described in the talps model (Belton et al. 2007a, 2007b), before comets even entered the inner solar system. Deep-seated global-scale layering of the composition has been observed on 9P/Tempel 1 and 67P/Churyumov-Gerasimenko (Thomas et al. 2007; Thomas et al. 2013a; Sierks et al. 2014). Whether their origin is primordial, evolutionary, or a mixture of both remains to be understood via additional observational constraints. We can thus expect that the coming ESA/Rosetta results, with the first determination of a comet internal structure, and the monitoring of surface features and activity, will shed some new light on the evolution of comet nuclei as well as a better understanding of their formation.

Acknowledgement This paper was triggered by a workshop initiated by A. Guilbert-Lepoutre on surface-interior interactions on small bodies, and funded by the ESTEC Faculty Council. The authors thus acknowledge J. Benkhoff, J. Blum, F. Cipriani, J. Deller, B. Gundlach, D. Heisselman, E. Lellouch and J.-B. Vincent for the fruitful discussions that lead to this manuscript. A. Guilbert-Lepoutre and S. Besse were supported by the European Space Agency Research Fellowship program. O. Mousis acknowledges support from CNES. This work has been supported by the A∗MIDEX project (n^{o} ANR-11-IDEX-0001-02) funded by the "Investissements d'Avenir" French Government program, managed by the French National Research Agency (ANR). M. Ali-Dib was supported by a PhD grant from the city of Besancon, France.

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