Unexpected and significant findings in comet 67P/Churyumov–Gerasimenko: an interdisciplinary view

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ABSTRACT

ESA's Rosetta Mission has followed Comet 67P/Churyumov–Gerasimenko from 3.6 au inbound to 3.6 au outbound. Many results are largely unexpected, as compared to previous models based on in situ and ground-based observations of Jupiter-family comets. The main topics discussed in this review are (1) the importance of the large concavities characterizing the 67P nucleus, that, (2) coupled to the nucleus obliquity, make seasons an unexpectedly important source of many phenomena observed in this and probably in most comets; (3) the mostly uniform distribution of ices over the nucleus surface; (4) the high dust-to-water mass ratio, which implies that much of the nucleus mass is in the form of minerals partly coming from the inner proto-solar nebula, thus making 67P very porous and less hydrated than primitive CI chondrites. 67P nucleus may have never experienced any collision at speeds larger than 1 m s^{-1}.

Key words: space vehicles – comets: general – comets: individual: 67P/Churyumov–Gerasimenko.

1 INTRODUCTION

ESA's Rosetta Mission has followed the nucleus of short-period comet 67P/Churyumov–Gerasimenko (hereinafter 67P) from 2014 August to 2016 September. On 2014 November 12, Rosetta deployed the Philae lander on the surface of the comet nucleus. Hundreds of papers are reporting scientific results, making necessary attempts at synthesis and reviews. Here we try the first, focusing on the most unexpected results which may introduce important changes in this branch of Solar system research, thus making the unexpected also significant. There is always an inextricable link among observations, data and models, which in short may be called a paradigm. Models allow us to plan observations, and the data from observations allow us to confirm, evolve or abandon our models. The topics covered in this synthesis are a selection of some examples of how our paradigm for comets may evolve after the Rosetta Mission.

Russell, Glassmeier & Boehnhardt (2007) provide a set of papers describing in detail all the Rosetta instruments. Here we discuss the results of the orbiter instruments: an imaging system with narrow-band filters (OSIRIS), and three spectrometers covering the whole radiation spectrum, ultraviolet (UV, Alice), Visible and IR with Imaging (VIRTIS), sub-mm and mm (MIRO); in situ gas mass spectrometers (ROSINA RTOF and DFMS), sensors measuring the gas pressure (ROSINA COPS) and the mass, speed and cross-section of individual dust particles (GIADA), an atomic-force microscope (MIDAS), a dust mass spectrometer (COSIMA); plasma instruments (RPC), Radar (CONSERT) and Doppler-radio (RSI) experiments. These results are complemented by some lander instruments: a camera (ROLIS), a gas mass spectrometer (PTOLEMY), and sensors of the compressive strength (MUPUS) and of the magnetic field (ROMAP).

2 THE NUCLEUS SHAPE

The shape of the nucleus of 67P (Preusker et al. 2015; Thomas et al. 2015a) was largely unexpected. The technique used to predict the nucleus shape is the inversion of the light curves provided by ground-based observations (Kaasalainen & Viikinkoski 2012). This method assumes convex bodies, a fact inconsistent with many comet nuclei we have visited in situ, which show a bilobate shape. Lamy

et al. (2007) estimated 67P's nucleus shape by the inversion of a single light curve. Later, Lowry et al. (2012) inverted many light curves collected during the prior aphelion passage, and the obtained shape is not far from the real one after filling the huge concavities to obtain a convex shape. A result is that the volume of 67P's nucleus was largely overestimated, affecting the predictions of the performances of the RSI experiment (Pätzold et al. 2016). If far from a sphere, the shape of a cometary nucleus is the dominant parameter affecting all physical models of the interaction between nucleus and coma (Crifo et al. 2004) and greatly enhances the coma heterogeneity with respect to that on the nucleus surface (Fougere et al. 2016).

3 A HIGH DUST-TO-WATER RATIO

The dust-to-water mass ratio is a fundamental parameter governing cometary activity and constraining 67P's origin. Data collected in the coma allow us to infer the average dust and water-vapour mass-loss rates from the sunlit nucleus surface. The dust-to-water mass ratio is provided by the ratio between these loss rates, so that it is defined at the sunlit nucleus surface. When computed in this way, the dust-to-water ratio is a lower limit, because it does not take into account the contribution of the largest dust masses unable to leave the nucleus, or falling back to the nucleus due to gravity. The 67P nucleus has a dust-to-water mass ratio of six from 3.6 au to perihelion (Rotundi et al. 2015; Fulle et al. 2016). At perihelion and just after, the dust-to-water mass ratio ranges from 6 to 100 (Fulle et al. 2016). The dust-to-water ratio has been inferred by individual particle detections by the GIADA and OSIRIS instruments (Rotundi et al. 2015). The 67P dust coma shows an extreme day/night asymmetry (Della Corte et al. 2015), so that the dust-to-water ratio has been extracted from observations obtained in the coma day side only, where the dust space density provides a sufficient signal.

GIADA determines directly the dust particle mass. In case of OSIRIS detections of larger particles, the observed cross-section has been converted to a mass assuming the bulk densities inferred by GIADA (Rotundi et al. 2015), ranging from 800 to 3000 kg m^{-3}. The dust particles are compact, i.e. denser than the nucleus of 67P, and similar to the non-fragmenting particles, composed of multiple minerals that produced carrot-shaped tracks in the aerogel of the Stardust collector (Brownlee et al. 2006; Della Corte et al. 2015). OSIRIS has observed the largest chunks escaping the nucleus gravity, ranging from cm-sized pebbles at 3.5 au inbound (Rotundi et al. 2015), to metre-sized chunks at perihelion (Fulle et al. 2016). The time periods during which particles were detected range from many hours to days, averaging the strong diurnal variations observed in the coma (Hässig et al. 2015). At 3.5 au inbound, assuming dust of radius of 0.3 mm and bulk density of 470 kg m^{-3}, Marschall et al. (2016) fit OSIRIS dust coma images and ROSINA-COPS gas data with a dust-to-gas ratio of two. Taking into account the abundance of minor species (Hässig et al. 2015), and the dust bulk densities provided by GIADA at half-mm sizes (Rotundi et al. 2015), the dust-to-gas ratio of two becomes a dust-to-water ratio ranging from four to eight.

With a dust-to-water ratio of six, the nucleus erosion at perihelion ranges from 1 m on average (Bertaux 2015) to 15 m locally (Keller et al. 2015b). The value of the dust-to-water ratio inferred just after perihelion refers to internal layers of the 67P nucleus, exposed by the erosion during perihelion. A dust-to-water ratio of six suggests a water ice content in 67P close to 15 per cent averaged over all the nucleus surface. With an averaged nucleus bulk density of 533 kg m^{-3} (Pätzold et al. 2016), and most of the dust mass in compact particles of 2000 kg m^{-3} on average (Rotundi et al. 2015), mass and volume concentrations are very similar both for ice and non-volatiles. VIRTIS observes less than 1 per cent of volume concentration of water ice averaged over the nucleus surface (Capaccioni et al. 2015), and at most 4 per cent in some few bright spots (Filacchione et al. 2016). At sunrise, VIRTIS observes up to 15 per cent of water ice on the surface of the Hapi smooth plain (De Sanctis et al. 2015), a nucleus region close to the northern pole (Thomas et al. 2015a). This water is coming from 67P's interior and is frozen inside the cold upper surface layers during the night (De Sanctis et al. 2015).

A large dust-to-water mass ratio implies that the nucleus matrix is non-volatile, so that ground-based experiments (Grün et al. 1993) and thermo-physical models of cometary nuclei (Prialnik, Benkoff & Podolak 2004), assuming an ice matrix, may provide misleading results: they should be repeated assuming a refractory matrix, which has micro-properties far from ices. The larger the dust-to-water ratio, the larger the porosity required to fit the observed nucleus bulk density. The RSI (Pätzold et al. 2016) and the CONSERT (Kofman et al. 2015) experiments exclude macro-porosity at scales above 100 m. CONSERT experiment provides a micro-porosity between 75 per cent and 85 per cent (Kofman et al. 2015). Hapke models provide a surface porosity of 87 per cent (Fornasier et al. 2015). Since most dust mass is in form of compact particles of size > 1 mm (Fulle et al. 2016), a significant fraction of the nucleus porosity must have a scale > 1 mm. A dust-to-water ratio of six, taking into account the abundances of minor species (Hässig et al. 2015), becomes a dust-to-gas ratio of four at 3.5 au, and of five at perihelion. Elemental abundances of CI chondrites imply a dust-to-gas mass ratio of three and a porosity of 70 per cent (Davidsson et al. 2016). The region of the proto-solar nebula where 67P accreted may have been drier than those where CI chondrites have formed.

4 ACTIVE AREAS HARD TO FIND

Coma features have always been modelled in terms of water and dust ejection from the nucleus surface (Crifo et al. 2004). For most comets, ground-based observations cannot define the nucleus shape, which in most cases was simplified to a sphere. If the nucleus shape is far from a sphere, its topography becomes the most important source of coma features (Crifo et al. 2004). Many comet nuclei observed in situ show a bilobate shape, very far indeed from a sphere. This implies that ground-based observations should not be used to infer how dust and gas is ejected from the nucleus of a comet. Nevertheless, it is a traditional assumption, derived from ground-based observations, that gas and dust are ejected from small spots only, rich in water and other ices and covering a minor fraction of the nucleus surface; these were called 'active areas' (Lamy et al. 2007).

The Rosetta Mission is the first to provide the complete shape of a comet nucleus, which is, with its huge concavities, quite far from a sphere. Comet 67P is the first comet nucleus where the hypothesis of active areas can be tested, and this test must be performed by means of rigorous full 3D coma models, using Monte Carlo and gas-dynamical codes. At least three independent teams are developing such codes in the context of the Rosetta Mission: LATMOS code (Zakharov, Rodionov & Crifo 2009), ICES code (Bieler et al. 2015b; Fougere et al. 2016), and Bern–Taiwan code (Lin et al. 2016; Marschall et al. 2016). Surprisingly, all the three teams have obtained a good fit of the large diurnal variations of the gas flux

observed by ROSINA-COPS (Bieler et al. 2015b; Hässig et al. 2015), starting from the opposite assumption of active areas: the whole nucleus surface has a uniform distribution of dirty water ice, with the northern hemi-nucleus at most three times more water ice-rich than the southern hemi-nucleus (Bieler et al. 2015b). The ICES team has refined this result by testing a dirty water ice distribution left free to assume many maxima and minima, by means of spherical harmonics expansion, and constrained by ROSINA-DFMS data and images of the water gas coma provided by VIRTIS (Migliorini et al. 2016). The result is the same: the nucleus surface has a uniform distribution of dirty water ice, with fluctuations below a factor of 3 (Fougere et al. 2016); only a single active area has been identified in the Hapi smooth plain, at most 10 times more rich in dirty water ice than most of the surface. A similar conclusion has been reached by the Bern–Taiwan team fitting ROSINA-COPS data and OSIRIS dust coma images at 3.5 au inbound (Marschall et al. 2016).

The results of the 3D coma models take their full meaning in the context of their assumptions. The most important one is the mesh size on the nucleus surface: due to the limited available cpu time, all the 3D coma models have a resolution at the nucleus surface of about 50 m. This limitation has two fundamental consequences. The first is that we cannot exclude active areas smaller than 50 m. This scenario would be anyway very far from the traditional view of a comet nucleus, characterized by at most a few (tens of) active areas: 67P may have thousands of active areas with a uniform spatial distribution. The second consequence is more important: at the poor resolution of 50 m, the vector perpendicular to the nucleus mesh, which determines the local insolation (i.e. the water-loss rate), can be very far from the average direction of all the real vectors perpendicular to the local surface inside the mesh. Roughness effects are completely lost at 50 m resolution, and this affects the primary engine of cometary activity, i.e. the solar flux absorbed by the nucleus surface. 3D coma models have still to fit the observed dust coma features, which have a scale much lower than gas coma features, often below the 50 m resolution (Vincent et al. 2016). In order to model the dust coma, 3D coma models need to input how dust and gas interact at the nucleus surface: the Rosetta Mission is still missing this information. How dust can leave the nucleus surface is still not understood (Gundlach et al. 2015). All Rosetta dust data collected before perihelion show that the optical dominant size ranges are from 0.1 to 1 mm (Rotundi et al. 2015; Fulle et al. 2016; Lin et al. 2016; Marschall et al. 2016). The slow motion of this dust makes necessary to take into account the nucleus rotation (Marschall et al. 2016) by means of time-dependent 3D coma models, developed by the LATMOS team only.

In contrast with these results, Vincent et al. (2016) suggest that water and dust release is concentrated in cliffs. Cliffs cover uniformly from 10 per cent to 15 per cent of the northern hemi-nucleus (Keller et al. 2015b). If the area covered by the cliffs is divided by the dust-to-water ratio, we get a cliff-to-total surface area close to 2 per cent, which is exactly what is needed to explain the observed total water flux (Keller et al. 2015b). The hypothesis that only cliffs eject water is a limit assumption. 3D coma models (Bieler et al. 2015b; Fougere et al. 2016; Marschall et al. 2016) may be unable to disentangle between a uniform water ice distribution, and ice concentrated in areas randomly covering 15 per cent of the nucleus surface. A test of the hypothesis by Vincent et al. (2016) by means of the 3D coma models is currently unreachable, given the mesh size adopted on the nucleus surface (50 m). For the cliffs, at this resolution, the nucleus shape model is affected by large errors in the orientation of the vector perpendicular to each mesh, which implies large errors of the insolation of the meshes crossed by the cliffs. The large diurnal variations of the ROSINA-COPS gas flux require a very good phase match between data and model. Cliffs have, by definition, a different time phasing of the insolation with respect to the surrounding plains. 3D coma models assuming a uniform distribution of dirty water ice at once match the observed times of maxima and minima of the ROSINA-COPS data (Bieler et al. 2015b). This suggests that the hypothesis by Vincent et al. (2016) may prevent 3D coma models from obtaining a good fit to the ROSINA-COPS data. Self-illumination of cliffs from surrounding plains may mitigate this effect (Keller et al. 2015b).

All Rosetta data indicate that water is ejected from all kinds of terrains. PTOLEMY (Wright et al. 2015) onboard Philae has observed water just after the first landing on a smooth plain. A quantitative analysis of the observed water flux is still lacking, so that this water might even come from very far cliffs. MIRO's nucleus thermal model indicates that, above $+40°$ latitude, water sublimation is necessary to explain the observed temperature, 20K lower than computed assuming a non-sublimating terrain (Schloerb et al. 2015). This water sublimation is observed everywhere. VIRTIS observed the largest concentration of water ice (up to 15 per cent) in the Hapi smooth plains (De Sanctis et al. 2015), which may explain the water ice peak inferred in the same region by 3D coma models (Fougere et al. 2016; Marschall et al. 2016). The dust size distribution at the nucleus surface inferred in the 67P coma (Rotundi et al. 2015; Fulle et al. 2016) matches that observed in the smooth plains (Mottola et al. 2015). Outgassing from an uniform water ice distribution fits the evolution of the nucleus rotation period, decreasing by 20 min every perihelion (Keller et al. 2015a).

5 NO DISTRIBUTED WATER SOURCES

The sources of water vapour and other gases can be the nucleus surface and the dust particles in the coma. In the second case, they are referred to as distributed sources. It is a tradition derived from ground-based observations to infer the presence of distributed sources when the gas column density is a power law of the nucleus distance with an index shallower than -1. Rubin et al. (2011) have shown that this approach (applied to coma gas density when the index is shallower than -2) is misleading when applied to in situ data. One of the reasons is again linked to the nucleus shape, which makes the diurnal variations of the local gas density larger than those due to the nucleus distance. In order to infer distributed sources from gas data collected in situ, we must again rely on 3D coma models. A comet where most water is coming from distributed sources is 103P/Hartley 2 (103P hereinafter). The water-loss rate observed from the ground is 9×10^{27} mol s^{-1} (Combi et al. 2011). At the same time, 3D coma models infer a total flux from the nucleus surface of 2×10^{27} mol s^{-1} and a ratio between night and sub-solar water loss of 30 per cent (Fougere et al. 2013).

For 67P, the water-loss rate observed from the ground (Keller et al. 2015b) matches that inferred at the nucleus surface by 3D coma models (Fougere et al. 2016). The night-to-day water-loss ratio assumed by 3D coma models at the nucleus surface is 2 per cent. This night water-loss rate is an ad hoc assumption adopted to fit the ROSINA-COPS data collected at the terminator, and cannot come from the entire night-side nucleus surface: its temperature is too low to eject so much water (Choukroun et al. 2015). It may come from the surface just after sunset due to its thermal lag (Shi et al. 2016), or from distributed sources. Assuming a process similar to that occurring in 103P, where 80 per cent of water from distributed sources requires a night-to-sub-solar ratio of the water-loss rate at

the surface of 30 per cent (Fougere et al. 2013), we can conclude that in 67P, at most 5 per cent of water is coming from distributed sources. This conclusion is consistent with the accuracy of the observed 67P water-loss rate. This water content is much lower than the dust-to-water mass ratio of six in the nucleus. Comet 67P ejects very dry dust, where with dry, we define dust containing less water than 15 per cent of its mass (dust is wet in the opposite case).

From Earth (Fulle et al. 2010; Moreno et al. 2016) and from Rosetta (Rotundi et al. 2015; Fulle et al. 2016) we observe the same dust-loss rate, thus excluding that dust releases a significant water mass. A sublimating and/or fragmenting particle decreases its mass during its travel in space, implying a strong change in the dust size distribution from the nucleus surface to Rosetta, and from Rosetta to the outer coma observed from ground. The dust size distributions at the nucleus surface observed in the smooth plains by ROLIS (Mottola et al. 2015), inferred from Rosetta observations (Rotundi et al. 2015; Fulle et al. 2016), and inferred from ground-based observations (Fulle et al. 2010; Moreno et al. 2016), do not show any systematic shift from large to small sizes. COSIMA observes dry dust (Schulz et al. 2015). Dust in 67P's coma does neither sublimate nor fragment more than 5 per cent of its mass, confirming that most dust mass is ejected in compact particles.

6 SEASONS DRIVE ACTUAL ACTIVITY

The importance of seasons in comets was understood decades ago (Weissman 1987), but what makes seasons so unexpectedly important in 67P is the coupling of nucleus spin obliquity to nucleus shape. Although the distribution of ices on the nucleus surface is mostly uniform, the nucleus concavities build-up a coma with strong differences in gas density. Since the nucleus sunlit area varies by more than a factor of 2, the coma gas density variations are further enhanced. The 67P coma shows strong diurnal and seasonal variations. Since the CO_2 ice distribution is opposite with respect to water, with a peak in the southern hemi-nucleus (Fougere et al. 2016), the diurnal cycles of water and CO_2 observed in 67P's coma may be sometimes in opposite phase, sometimes in the same phase (Hässig et al. 2015; Fougere et al. 2016). It is evident that it would be impossible to infer the nucleus heterogeneity from coma observations without knowing the nucleus shape. This suggests that ground-based observations of chemical abundances in comets may be affected by a large bias, if the observations do not cover both the full diurnal cycle and all seasons, i.e. the full comet orbit (A'Hearn 2004, Section 3.1).

What is observed in 67P casts dark shadows on what we can learn from only snapshots of nucleus activity and coma state. A good example of how snapshots may be misleading is provided by the dust fluence measured during flybys to comets, which was observed to be similar in comets 1P/Halley (McDonnell et al. 1990), 26P/Grigg–Skjellerup (McDonnell et al. 1993), 81P/Wild 2 (Green et al. 2004) and 9P/Tempel 1 (Economou et al. 2013). It is hard to imagine a process more chaotic than dust ejection from a nucleus surface, which in fact is still not understood (Gundlach et al. 2015). It is probable that the dust size distribution evolves with seasons, a fact confirmed in 67P (Fulle et al. 2016). The fact that four snapshots at four different comets provided similar dust size distributions is almost a proof that the four dust fluences are affected by the same strong bias, which is well known (Fulle et al. 1995, 2000). The dust size distributions at the nucleus surface of 1P/Halley, 26P/Grigg–Skjellerup, 81P/Wild 2 and 9P/Tempel 1 remain undefined. The dust

size distribution of a comet is a time-dependent parameter (Fulle 2004).

A fundamental effect of seasons in 67P is the dust transfer from the southern hemi-nucleus (mostly active at perihelion during the short summer from 1.7 au inbound to 2.6 au outbound) to the northern hemi-nucleus (mostly in night at perihelion but active at Rosetta arrival at 3.8 au in 2014). Dust transfer is the probable source of the smooth plains covering much of the northern hemi-nucleus (Keller et al. 2015b; Mottola et al. 2015; Thomas et al. 2015b) and lacking around the southern pole. It explains the match between the dust size distributions observed by ROLIS (Mottola et al. 2015) and by OSIRIS at sizes larger than 1 mm (Rotundi et al. 2015), and also the time evolution of the dust size distribution at sizes smaller than 1 mm observed by GIADA (Fulle et al. 2016). At perihelion, the southern hemi-nucleus ejects dust with a size distribution close to a power law with a differential index of −4. Dust smaller than 1 mm, falling back on the northern hemi-nucleus mostly in night, is affected by the low gas density in the night coma: the smaller the dust, the more improbable for it to reach the nucleus surface. This makes the dust size distribution of the northern hemi-nucleus much shallower (Fulle et al. 2016), with a power index between −2 and −3 at sizes <1 mm.

The dust transfer from south to north has a fundamental consequence. Since the falling dust is dry, the smooth plains must be dry in all their thickness, from 0.2 m (Biele et al. 2015) to metres in Hapi, which may be the main dust source beyond 2.5 au inbound (Della Corte et al. 2015). This is a striking paradox, because VIRTIS has observed the largest water concentration exactly in Hapi (De Sanctis et al. 2015). The easiest (not necessarily true) way to solve this paradox is to redefine when dust is dry. If we assume that the dust-to-water ratio in the southern hemi-nucleus is 20 (i.e. consistent with the range from 6 to 100 measured at perihelion; Fulle et al. 2016), then dust with 5 per cent or more of mass in water ice becomes wet. Smooth plains, made of deposits of wet dust, become wet. Also, the VIRTIS water upper limit of 1 per cent averaged over the whole nucleus surface becomes consistent with a wet surface, by assuming a factor of 5 as bias due to the dust layer hiding the ice. This bias is still consistent with the water concentration measured in Hapi. The water transfer from depth to surface during the night may increase the water concentration from the average of 5 per cent up to 15 per cent ($\times 5 = 75$ per cent) just below the surface as observed by VIRTIS just after sunrise (De Sanctis et al. 2015). The lower dust-to-gas ratio of six inferred from coma dust detections at 3.5 au inbound (Rotundi et al. 2015; Marschall et al. 2016) would be biased by the dust mass that the gas coma can lift-up, leaving the largest wet dust on the surface. Groussin et al. (2015b) observe the collapse of wide plains in the Imhotep region, sinking much faster than predicted by water sublimation. They suggest a destabilization of the collapse boundaries by phase transition of amorphous ice. Mousis et al. (2016) exclude abundant amorphous ice in 67P. A dust-to-water mass ratio of 20 would increase the total volume ejected during water sublimation to such an extent to approach the volume changes observed in Imhotep region.

7 THERMO-PHYSICAL MODELS FAIL

The 67P surface has a very low thermal inertia, close to 20 J K^{-1} m^{-2} s$^{-0.5}$ (Schloerb et al. 2015), which is probably due to the porosity at scale >1 mm among the compact particles mainly composing the nucleus surface layer. At 3.5 au inbound, the highest surface temperature is $T = 230$ K (Capaccioni et al. 2015); at a depth of 1.5 cm it is $T = 180$ K, and at a depth of 5 cm, it is $T = 160$ K

(Gulkis et al. 2015). In this range of temperatures, the water-loss rate $Q(T)$ is well approximated by $Q(T_1)/Q(T_2) = 10^{0.07(T_1-T_2)}$ (Andreas 2007). Even if the nucleus were composed of pure ice from a depth of 1.5 cm downwards, the entire surface of 67P would release a negligible water fraction of that observed (Gulkis et al. 2015; Keller et al. 2015b). This proves that all the water-vapour is coming from the uppermost surface layer thinner than 1 cm, i.e. the size of the largest pebbles ejected at 3.6 au inbound (Rotundi et al. 2015), and a factor of 100 thinner than the metre-sized chunks ejected at perihelion (Fulle et al. 2016). This fact further suggests that a force independent of vapour pressure is breaking the link between dust and the nucleus surface, after which the dust is accelerated in the coma by vapour drag. A second consequence is that local thermo-dynamical equilibrium (LTE) cannot be applied in models of water and dust ejection from comets. The fact that all thermo-physical models of comets assume LTE (Prialnik et al. 2004) may explain why they fail most predictions.

Prialnik et al. (2004) write that thermo-physical models of comets predict the formation of 'a dust mantle which inhibits gas sublimation when most of the surface is covered by dust (Prialnik & Bar-nun 1988), a result confirmed by the KOSI experiment (Grün et al. 1993)'. VIRTIS observes this mantle: the surface of 67P is covered by an organic-rich layer (Capaccioni et al. 2015), where the few wettest spots contain at most 4 per cent water (Filacchione et al. 2016), but 67P is still very alive. This confirms that some results of the KOSI experiment, based on a dust-to-water ratio lower than one, are misleading. Thermo-physical models predict a dependence of the water-loss rate on the heliocentric distance which is a power law with index of -2 inside 2.5 au, and much steeper beyond (De Sanctis, Capria & Coradini 2006; Gortsas et al. 2011). 67P's water-loss rate follows a power law of the heliocentric distance with a constant index of -4.2 from 3.8 au to perihelion (Fougere et al. 2016). At 3.5 au inbound, thermo-physical models predict a constant temperature at a depth of 4 cm (De Sanctis et al. 2015), blind to the diurnal cycle. At a depth of 5 cm, MIRO observes a diurnal oscillation of 20K (Gulkis et al. 2015), probably due to the surface roughness linked to the ejection of dust of similar size. A dust layer much thinner than the size of the ejected dust has little physical sense, but is still a common assumption of models of water ejection (Keller et al. 2015b).

8 67P ORIGIN AND COLLISIONAL HISTORY

Decades ago, Weissman (1986) suggested that comets are primordial rubble piles, formed by the gentle accretion of cometesimals, without strong modifications occurring during the later collisional phase. This scenario is at odds with some of the current models of early Solar system evolution, where comets are collisional rubble piles (Morbidelli & Rickman 2015). Rickman et al. (2015) show that the shape of 67P is due to the accretion of two lobes at speeds less than 20 m s^{-1}, in order to preserve the low nucleus bulk density (Pätzold et al. 2016). The two lobes may be primordial rubble piles, or rubble piles of collisional fragments, as suggested by parallel cracks observed in Hathor region (Rickman et al. 2015). Massironi et al. (2015) detect layers of unknown origin with independent orientation in the two lobes, some hundred metres thick in the Seth and Hathor regions.

Davidsson et al. (2016) reconcile the two possible scenarios of 67P formation. The outer proto-solar nebula is assumed to have a mass of 15 Earth masses, the lower limit still consistent with the Nice Model. Cometesimals are accreted at speeds <2 m s^{-1} in the first 4 Myr up to sizes of 1 km. The slow growth makes

possible the collection of the mineral aggregates coming from the inner Solar system and observed in 81P/Wild 2 (Brownlee et al. 2006) and 67P (Rotundi et al. 2015), and prevents the loss of supervolatiles during the decay of short-lived radionuclides. Ciesla (2011) shows that the transfer of mineral aggregates processed in the inner proto-solar nebula takes less than 1 Myr, thus not requiring a slow 67P accretion. Davidsson et al. (2016) assume that all the non-volatile mass of the 67P nucleus is coming from fractal aggregates formed in the outer proto-solar nebula, and then compressed to the porosity observed now in 67P by the slow accretion. This assumption neglects the dominant mass contribution of mineral aggregates (Rotundi et al. 2015), which explains the 67P bulk density (Pätzold et al. 2016) as the natural average between the bulk density of minerals and the porosity of local fractals or even voids (Fulle et al. 2015).

According to Davidsson et al. (2016), 'mild accretion velocities up to 50 m s^{-1} and the absence of aqueous alteration have kept destructive forces to a minimum. These late collisions among km-sized cometesimals build-up 100-m deep layers by gentle compression, without modifying the homogeneous and porous structure of the blocks building-up the final nucleus, characterized by a crust of enhanced bulk density'. The CONSERT experiment does not confirm the increase of bulk density close to the nucleus surface (Kofman et al. 2015). There is still no consensus on the fact that layers are structures continuing in the nucleus interior up to depths of some hundreds metres (Thomas et al. 2015a). Dust transfer from the southern to the northern hemi-nucleus builds-up layers by itself (Thomas et al. 2015b). No layers are seen in the walls of the sinkhole collapse pits on the nucleus surface (Vincent et al. 2015). Observations of boulder collapse at the layer edges do not confirm any increase of tensile strength in the layers (Groussin et al. 2015a). The unexpected high compressive strength >4 MPa observed in the final Philae landing spot by MUPUS (Spohn et al. 2015) suggests sintering of organic dust due to the thermal processing by solar heating (Biele et al. 2015), and is not considered primitive. Comet 67P is the first where we could detect pits, about 100 m wide and deep (Vincent et al. 2015). The pits are windows open to the nucleus interior, and show goosebump features in their walls (Sierks et al. 2015). The size of these features (3 m) matches that predicted for the most resilient cometesimals during the first accretion (Davidsson et al. 2016). If the goosebumps are primitive and will be confirmed in images at better resolution, the 67P nucleus macro-porosity should have a similar scale, not observable by the Rosetta instruments.

The fluffy dust particles detected by GIADA (Fulle et al. 2015), which have the equivalent bulk density of air (<1 kg m^{-3}) and sizes up to a few mm, provide one of the most stringent constraints selecting the working model of 67P's origin. According to Fulle et al. (2015), the fluffy aggregates are charged by the secondary electron flux from Rosetta, and then fragmented and decelerated by the electrostatic interaction between the fragments and Rosetta, down to speeds of a few cm s^{-1}. At these speeds, the fragments provide exactly the kinetic energy ranging from 0.2 to 20 keV of some electron bursts observed by the RPC/IES experiment (Burch et al. 2015), and interpreted in terms of nm-sized dust (Gombosi, Burch & Horanyi 2015). The dust deceleration by the weak Rosetta electric field requires a charge-to-mass ratio >1 C kg^{-1}, implying a bulk density <1 kg m^{-3} at the observed cross-sections of the fluffy aggregates (Fulle et al. 2015). The predicted fractal dimension of the fluffy aggregates is $D = \log N/\log R/r = 1.87$ (where $N \approx 10^6$ is the number of grains of radius $r = 0.1$ μm building-up fluffy aggregates of radius $R = 160$ μm; Fulle et al. 2015), close to the

fractal dimension $D = 1.75$ measured in analogues of interplanetary dust particles (IDPs; Katyal, Banerjee & Puri 2014), and in real IDPs (Rietmeijer 1993). The MIDAS experiment onboard Rosetta (Bentley et al. 2016) can provide 3D images of dust aggregates with a resolution better than 0.1 μm.

The dust bulk densities show a huge gap between fluffy and compact particles. Beyond 2.5 au inbound, compact particles come mainly from the neck, whereas fluffy particles are uniformly distributed over all the nucleus (Della Corte et al. 2015). Fluffy particles contribute to ≈15 per cent of the total non-volatile volume, but to a negligible fraction of the ejected mass (<1 per cent). These facts suggest that they represent the primitive proto-solar component, having survived during the initial accretion of 67P in the voids among the pebbles, thus excluding impact speeds larger than 1 m s^{-1} during the whole 67P accretion history (Güttler et al. 2010). This upper limit of the collision speeds confirms that comets were accreted by the gentle gravitational collapse of a cloud of cm-sized pebbles (consistent with the compact particles observed by GIADA), confined in a Hill sphere by the flow instabilities at the end of the proto-planetary nebula gas phase (Wahlberg Jansson & Johansen 2014).

9 FIRST LINK TO MOLECULAR CLOUDS

The D/H ratio in water is a powerful tool to infer at which temperature and time the water was trapped in comets. It varies from the extremes of 0.0015 per cent in the local interstellar medium (Hartogh et al. 2011), to 0.1 per cent–1 per cent in dense molecular clouds (Teixeira et al. 1999). Earth's oceans and CI chondrites have an intermediate value, 0.016 per cent. Comet 67P is the first to approach the values observed in molecular clouds, with D/H = 0.053 per cent (Altwegg et al. 2015) in water. This value is consistent with a late 67P accretion and with ices frozen at very low temperatures, a fact confirmed by the concentrations of molecular nitrogen (Rubin et al. 2015) and oxygen (Bieler et al. 2015a). 103P has Earth's D/H value, even lower than Oort cloud comets (OCs), which have an average D/H = 0.03 per cent (Hartogh et al. 2011) in water. Although OCs and Jupiter family comets (JFCs) may have formed in the same region (Morbidelli & Rickman 2015), the two D/H samples of JFCs point out a wider D/H dispersion in JFCs than in OCs. The low D/H value of 103P may be due to an accretion in inner regions of the proto-solar nebula. 103P ejects much wetter dust than 67P (Fougere et al. 2013), suggesting a lower dust-to-gas ratio, opposite to that inferred by the D/H ratios. The chemical composition of comets may be independent of the accretion distance from the Sun, which may fix the D/H ratio only.

Molecular oxygen was completely unexpected in its high abundance of 4 per cent relative to water. It is highly reactive, suggesting an origin directly on the ice mantles of interstellar dust grains (Bieler et al. 2015a). The abundances of N$_2$ (Rubin et al. 2015), O$_2$ (Bieler et al. 2015a) and Argon (Balsiger et al. 2015), all supervolatiles, indicate that 67P never experienced high temperatures. In particular, if supervolatiles are trapped in amorphous water ice, 67P's temperature must have always been lower than 90 K, otherwise the amorphous water ice phase transition to crystalline ice would have depleted 67P of all supervolatiles. Mousis et al. (2016) find that supervolatiles are trapped in clathrates or possibly in crystalline ices. In this case, if supervolatiles are frozen in contact with water ice (Bar-nun et al. 1987), 67P cannot have been warmer than 40 K, in order to explain their observed abundances (Davidsson et al. 2016). The poor correlation between the outgassing of water and some supervolatiles (Luspay-Kuti et al. 2015) suggests that many

are not frozen in contact with water ice. In this case, the required temperature to store them becomes worryingly low, about 20 K (Bar-nun et al. 1987; Davidsson et al. 2016).

10 67P PLASMA

Rosetta has made the first observations of the birth of the interaction of the comet with the solar wind, with the detection of heavy ion and solar wind deflection near the comet (Nilsson et al. 2015). Already at the rendez-vous at 3.6 au, the comet plasma environment showed similar diurnal variation as the neutral gas (Odelstad et al. 2015), showing the domination of ionization of the neutral coma by UV radiation and photoelectron impact dissociation (Feldman 2015). The solar wind could still reach the nucleus and sputtering was observed (Wurz et al. 2015). A comet magnetosphere emerged, which excited instability-driven waves and turbulence in the surrounding plasma, and Rosetta observed a new type of wave at 67P (Richter et al. 2015), which classic pick-up instabilities were unable to explain. Combined observations by ROMAP on Philae and RPC-MAG on Rosetta demonstrated that the cometary nucleus has no intrinsic magnetic field (Auster et al. 2015). Around the approach to perihelion, the formation of a diamagnetic cavity, as observed at 1P/Halley by Giotto (Neubauer et al. 1986), but due to the lower activity of 67P, was expected at much closer distances, 50–100 km from the nucleus (Koenders et al. 2015). Navigation issues meant that Rosetta was flying trajectories above 150 km around perihelion, but still the cavity was detected (Götz et al. 2016a). It is not yet clear if this is related to activity or the dynamic nature of the boundary (Götz et al. 2016b).

11 CONCLUSIONS

The classical model of comets as dirty ice balls (Whipple 1950) has focused most models of comets on ices. The more we visit comets, the dustier they appear. With 67P's dust-to-water ratio of 6 (and possibly larger), it is now necessary to spend much more time in modelling the non-volatile matrices with a modest content of ices inside. Jean-Pierre Bibring proposes a new word naming this stuff, 'organic(e)s', where the modest content of ices (within brackets) well summarizes the dominant non-volatile component. Between the sizes of 0.1 and 1 mm, 99 per cent of the dust mass is in the form of compact particles, denser than the nucleus. This implies that much of the nucleus mass is in the form of mineral aggregates (silicates and sulfides), so that a better definition may be 'mineral organic(e)s'. The balanced analysis of ices, minerals and organic matter will help us to understand these objects and their origin. The Rosetta Mission confirms that 67P is an extreme mixture of volatile ices formed in very cold regions, and of minerals partly coming from the inner hot proto-solar nebula. The observed structure of the nucleus of 67P has already allowed us to better constrain how the scattered disc was formed. The dust particles detected by the Rosetta Mission are forcing us to a real change of paradigm, regarding which collisions really occurred during the accretion of the Solar system in and beyond the Uranus–Neptune region.

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