Cometary Nuclei—From Giotto to Rosetta

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Abstract We will briefly recapitulate the beginning of modern cometary physic. Then we will assess the results of the cometary flyby missions previous to ESA's Rosetta rendezvous with comet 67P/Churyumov–Gerasimenko. Emphasis is given to the physical properties of cometary nuclei. We will relate the results of the Rosetta mission to those of the flybys. A major conclusion is that the visited cometary nuclei seem to be alike but represent different stages of evolution. Coma composition and appearance are not only controlled by the composition of the nucleus but also strongly influenced by the shape and rotation axis orientation of the nucleus and resulting seasons that generate varying surface coverage by back fall material. Rosetta showed that the coma composition is not only varying spatially but also strongly with time during the perihelion passage. Hence past interpretations of cometary coma observations have to be re-considered. Finally, we will try to assess the impact of the cornerstone mission leading to a critical evaluation of the mission results. Lessons learned from Rosetta are discussed; major progress and open points in cometary research are reviewed.

Keywords Comets · 67P/Churyumov–Gerasimenko · Cometary nuclei · Rosetta mission

1 History of Cometary Physics

Comets display a unique spectacle on the night sky. Usually they appear like a faint star during their discovery and later move fast across the night sky becoming brighter when

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they are best seen in the early morning or late evening. They can become spectacular as diffuse objects sometimes covering a large part of the visible sky. But most of all their unpredictable appearance, their apparent size, and their similarly fast disappearing make these unique. They are intruders into the eternity and regularity of space. No wonder that they were considered harbingers of imminent disasters over centuries.

What sets comets apart from the fixed stars and the planets, slowly moving on regular orbits, is the diffuse appearance of their coma and frequently their long tails. They are so different that it was only consequent for Aristotle (384–322 BC) in his Cosmology to consider them not being members of the sky but as temporary exhalation of the earth's atmosphere (Heidarzadeh 2008). It took more than 1800 years before the parallax measurements by Tycho Brahe (1546–1601) positioned the Great Comet of 1577 beyond the orbit of the Moon. Comets were understood as members of our planetary system. It took another 100 years when Edmund Halley (1656–1742) predicted the return of a bright comet orbiting the Sun on a very elongated ellipse with a period of 75 years. This validated the law of gravity far beyond the realm of our planets suggesting its universal ruling.

But what is the physical nature of these strange wanderers in our planetary system? There are comprehensive reviews of the history of comets studies (Festou et al. 1993a, 2004) and therefore we mention only some highlights. G. Schiaparelli (1866) connected comets with meteor streams showing that their diffuse appearance is due to small dust particles within the coma. F.A. Bredikhin and F.W. Bessel developed their mechanical model of cometary tails based on a repulsive force from the sun that was later identified by S. Arrhenius (1900) as radiation pressure. In the second half of the 19th century the first spectroscopic observations were performed and revealed that carbon was an important constituent of comets. Schwarzschild and Kron (1911) explained the brightness distribution of the tail of comet 1P/Halley by fluorescence (absorption and reemission) of solar radiation. Only in 1941 P. Swings (Swings 1941) explained why the bright CN emission of the cometary coma differed from laboratory observations. A concentration of solar absorption lines influences the molecular bands according to the Doppler shift of the cometary velocity. Wurm (1943) developed his concept of "parent" molecules because the observed radicals and ions are not stable enough to survive storage in the nucleus.

In the fifties of the last century the foundations of our present day understanding of the nature of comets were created. Whipple (1950) modelled the cometary nucleus as a solid conglomerate of ices and imbedded dust (non-volatile compounds). About 40 years later the images of the nucleus of comet 1P/Halley strongly suggested that the matrix of the nucleus material was dominated by refractories, an icy dirtball rather than Whipple's dirty snowball Keller (1989).

Oort (1950) postulated a cometary reservoir at the fringes of the solar gravitational influence, and Biermann (1951) predicted the solar wind that is accelerating cometary ions into tails of small aberration angles, a ingenious interpretation that was confirmed by measurements of a lunar space probe in 1959.

New technologies in spectroscopy covering the extended wavelengths from the UV to IR, radio dishes and space borne observations provided the means for systematic and quantitative comet observations. A striking observational fact is that, at first sight, all comets look alike (Cochran et al. 1989; Festou et al. 1993b). There are, however, a few noticeable exceptions such as comet 29P/Schwassmann–Wachmann 1 (mainly CO^+) that display a completely different composition of the coma. In addition, no systematic changes of comets with evolution, not even a clear difference between new Oort cloud comets and Jupiter family comets could be established; see for instance the more recent discussion of the abundance of the highly volatile CO and CO_2 molecules by A'Hearn et al. (2012) and about the

D/H ratio (Altwegg and the ROSINA Team 2017). The situation was already reflected by Delsemme (1982) in the Comets book who concluded: Cometary material originating from different depth of the nuclei shows (a) the same dust to gas pattern, (b) the same spectral composition of the volatile fraction, (c) the same structural strength against fragmentation, and (d) the same vaporization pattern after fragmentation. Consequently cometary nuclei are homogeneous and show little variation—notwithstanding that there could be large surface differentiation effects during their aging. This was proven again in 2006 by observations of the split comet 73P/Schwassmann–Wachmann 3 (Dello Russo et al. 2007).

At that time the first missions to encounter comet 1P/Halley in 1986 were prepared. Of particular interest for the design of the mission instruments were the estimated sizes of cometary nuclei and their albedos. The results of Delsemme and Rud (1973) for the long period comets C/1969 T1 (Tago–Sato–Kosaka) albedo, $A = 0.6$ and radius, $R = 2.2$ km and C/1969 Y1 (Bennett) $A = 0.7$ and $R = 3.8$ km served as guideline for what was to be expected for 1P/Halley.

2 The Giotto and VEGA Missions (1P/Halley)

The upcoming reappearance of comet 1P/Halley excited public interest in reminiscence of its last spectacular passage near earth in 1910. This trigger and the generally strong interest in comets as witnesses of the physical and chemical conditions of the early solar system resulted in the proposal of the grandiose and technically advanced Halley Flyby/Tempel 2 Rendezvous mission, a collaboration of NASA and ESA, in 1979. Unfortunately, NASA had to withdraw from the endeavor due to budget cuts, but ESA designed its own dedicated mission, based on a GEOS spacecraft (earth orbiting). Cooperation with the Soviet Union missions VEGA 1 and 2 facilitated the aiming for a close flyby of the nucleus of comet 1P/Halley. The Giotto mission became ESA's first interplanetary mission and by its success opened the door to its further planetary research program. The worldwide enthusiasm helped to overcome the risks inherent in the super high flyby speed of 70 km/s and the very narrow launch window of less than 3 weeks.

Both three axis stabilized VEGA space probes passed the comet nucleus in several thousand kilometers distance after their successful flybys of planet Venus. Their camera systems were troubled by some technical problems. The VEGA 1 narrow angle camera was defocused. The dynamic range of the images of both cameras were severely limited caused by electronic problems (Merényi et al. 1990; Stooke and Abergel 1991). Hence it was up to the Giotto mission to reveal details of the nucleus of comet 1P/Halley providing images with a resolution down to 45 m per pixel. A comprehensive overview of the results of the nucleus of 1P/Halley claimed by the VEGA and Giotto probes is given by Keller (1990). The observational results of these missions confronted the model concepts developed over the previous decades with the reality and set the next step to our understanding of comets (see Newburn et al. 1991).

In particular

- Cometary nuclei are very dark (albedo 0.04) containing refractories, organic material, and ices (Keller et al. 1986; Kissel et al. 1986)
- The rough surface reaches nearly black body temperature (>360 K) what rules out large amounts of subliming ice on the surface (Emerich et al. 1987)
- Cometary nuclei are bigger than required to produce the observed water production rates (limited areas of sublimation or quenched activity)

- Cometary nuclei are porous and of low density and tensile strength
- Abundant super volatiles (CO, CO_2) require nucleus formation temperatures below 30 K
- Comets provide access to the most primitive (pristine) material out of which our solar system formed

3 The NASA Comet Flybys

After the success of the Halley campaign and during the preparation of Rosetta (see next chapter) NASA sent 3 spacecraft to 5 cometary flybys within a decade. DEEP SPACE 1 flew by comet 19P/Borrelly in 2001. It was followed by STARDUST to 81P/Wild 2 in 2004 and DEEP IMPACT to 9P/Tempel 1 in 2005. EPOXI (the renamed DEEP IMPACT) passed comet 103P/Hartley 2 in 2010 and STARDUST NEXT re-visited 9P/Tempel 1 in 2011.

DEEP SPACE 1 (19P/Borrelly)   The DEEP SPACE 1 images of 19P/Borrelly confirmed the impression that cometary nuclei do not dominantly consist of ice (dirty snowball) but that their topography and morphology are rough down to the scale of the resolution and probably beyond. On the well illuminated surface of the elongated nucleus geologic features such as mesas, pits, mottled terrain, ridges, and fractures could be discerned within varying units. No ice was observed on the surface. So the question how cometary activity works from beneath an inert layer of refractories became more mysterious but also more crucial for the understanding of cometary physics. Britt et al. (2004) suggested that the major but still relatively weak jet-like activity originated from collapsing walls of the prominent mesa-like formation near the rotation pole. The walls should not be covered by residual or back fall refractory material. Overall the nuclei of comets 1P and 19P seemed rather similar (e.g. the elongation and overall roughness). The major difference between both comets is their level of activity.

STARDUST (81P/Wild 2)   STARDUST was the first mission to bring cometary material back into Earth's laboratories. It flew through the coma of 81P/Wild 2 with a minimum distance of 236 km and collected particles in aerogel at a relative speed of 6 km/s (Brownlee et al. 2004). The minute amounts of cometary refractory material trapped in the aerogel foil triggered a burst of analytic papers that investigated the mineralogy and petrology. Overall the composition of the particles was found to be similar to that of CI chondrites with some excess of more volatile atoms. Highly processed material such as CA inclusions show that the material in the outer protoplanetary regime where comets formed was strongly mixed providing a large mineralogical diversity (Flynn 2008). Furthermore, Elsila et al. (2009) identified extraterrestrial glycine in the sample what was the first detection of a cometary amino acid.

Contrary to both earlier comets the shape of 81P is more spherical, its total volume is comparable to that of 19P/Borrelly. The topographic relief on 81P/Wild 2, however, is substantially rougher (>200 m) than that on Borrelly (about 100 m). Slopes on Wild 2 are steep, even overhangs are visible. The nucleus of 81P is evidently not a rubble pile but rather a solid body. The surface layers seem strong and cohesive relative to the gravitational force. This and the multitude of deep crater-like features suggest that 19P is more evolved than 81P that arrived in the inner solar system only 30 years before. The crater density lies beyond the saturation curve (Basilevsky and Keller 2006). The genesis of the craters is unclear but could possibly be attributed to impacts during the formation and early lifetime of the nucleus.

DEEP IMPACT (9P/Tempel 1)   Only one year later the DEEP IMPACT experiment and flyby of comet 9P/Tempel 1 took place. The prime goal of the mission was to observe possible compositional variations of cometary volatiles and to determine the structural properties and strength of the surface layers by excavating a crater on the cometary surface. This was done with a 372 kg impactor mainly made of copper that hit the surface with 10.2 km/s. Except for a slight increase in the CO_2/H_2O ratio no deviation from the ambient coma was found. Local gravitational field and average nucleus density (~ 600 kg/m^3) were estimated from ejecta fallback of particles in the range of 1 to 100 μm of negligible tensile strength (<65 Pa) (A'Hearn et al. 2005). This was later questioned by Holsapple and Housen (2006) who found that any strength from 0 to 12 kPa could furnish the ejecta data. The size of the crater, a measure of the physical properties of the ground, could not be derived after the impact since it was hidden by the ejecta.

The analysis of the ejecta spectra showed that water ice (and other species) were uniformly distributed below a transition layer of <1 m down to 10 to 20 m (Sunshine et al. 2007).

Only very thin patches of water frost could be detected on the surface (Sunshine et al. 2006). Relatively detailed temperature maps of the illuminated surface were achieved by scans with the IR spectrometer. Groussin et al. (2007) modelled the temperature maps and derived a very low value for the thermal inertia (< 50 W K^{-1} m^{-2} s$^{1/2}$). By using re-calibrated data (Davidsson et al. 2013) found terrains with thermal inertias up to 200 W K^{-1} m^{-2} s$^{1/2}$. Asymmetries of the coma were observed in the spatial distribution of CO_2 and H_2O indicating chemical heterogeneities within the nucleus (Feaga et al. 2007).

STARDUST NEXT (9P/Tempel 1)   After delivering its sample package the Stardust spacecraft was re-directed to perform a second flyby of 9P/Tempel 1 as STARDUST NEXT in 2011. This improved the determination of its nucleus shape, density, and geology in more detail (Thomas et al. 2013a). For the first time indications of interplay of erosion and depositions were suggested. No explanation for the strong erosional features could be given. Furthermore, the DEEP IMPACT crater, produced a cometary orbit ago, could now be estimated to be 49 ± 12 m in diameter (Richardson and Melosh 2013). It was surrounded by an area of slightly brightened material of 85–120 m in diameter yielding an effective target strength of 1–10 kPa. The Tempel 1 observational results, most model dependent, confirmed that cometary nuclei are of low density (see also Rickman et al. 1987), low tensile strength, low thermal inertia and are dominated by refractory material.

EPOXI (103P/Hartley 2)   The Deep Impact spacecraft was re-directed after its visit of Tempel 1 and the mission was re-named EPOXI. The images of comet 103P/Hartley 2 taken during the flyby of EPOXI in 2010 (A'Hearn et al. 2011) revealed its bilobate, elongated, nearly axially symmetric shape, 2.33 km in length. A smooth but variegated region forms a "waist" between the two lobes (Thomas et al. 2013b). It is covered by back fall of icy grains that do not contain any CO_2 anymore because this volatile ice can sublime even from the center of the grains. Bigger centimeter and decimeter size chunks, some with speeds above escape could be followed optically on their trajectories (Kelley et al. 2013). Most of the activity of the comet is driven by CO_2 sublimation which explains the hyperactivity by extended sources. More water is found in the coma than can be produced by water ice sublimation on the surface. Above the illuminated lobe icy grains driven by CO_2 sublimation strongly contribute to the coma signal. Above the waist, however, mainly water vapor and no CO_2 was observed.

In summary, the nuclei of the 5 comets (4 JFC comets) look quite diverse. Most of them suggest a bilobate origin. The morphology of the surface (where resolved) is quite different.
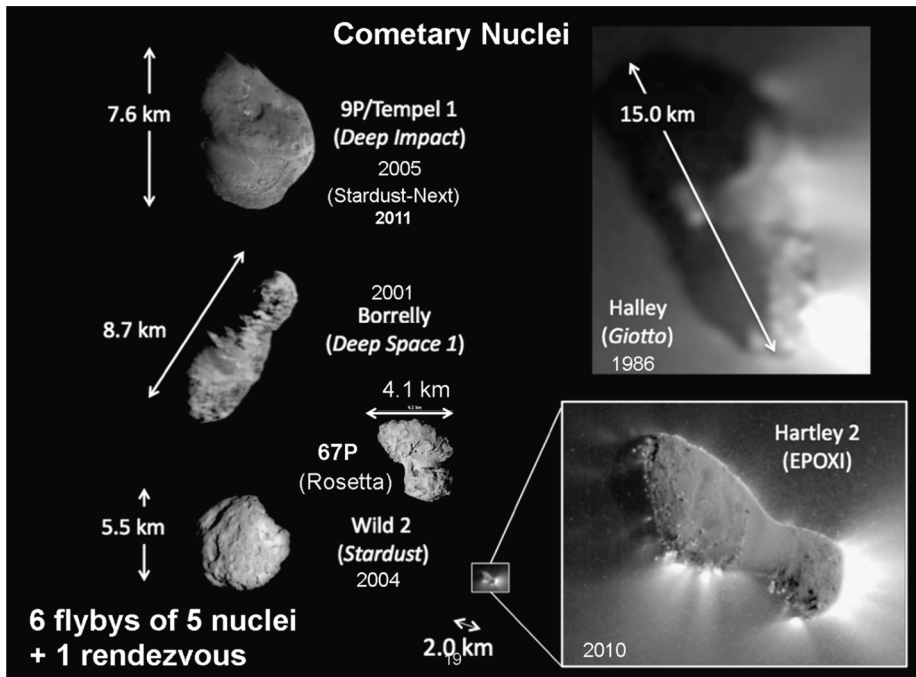
Fig. 1 Cometary nuclei imaged during flybys and by Rosetta

The strongly pitted (cratered) surface of 81P looks much different to the smooth terrains observed on 9P (Fig. 1). Their activity levels are very diverse, encompassing the absolutely high activity of 1P, the relatively high activity of the 103P to typically (for JFC comets) low activity of 9P. Are these nuclei intrinsically diverse or are their appearances an expression of their evolution? The Rosetta mission will provide the answer.

A summary of the missions, listing target, date of encounter, and distance of closest approach is given by Vincent et al. (2019) (Table 2) in this issue.

4 The Rosetta Mission

4.1 Background of the ESA Cornerstone Mission

The flybys of comet 1P/Halley had not even taken place when NASA and ESA appointed a science definition team to investigate a comet nucleus sample return mission (CNSR). Originally NASA did not consider comet flybys as scientifically rewarding. This was the major reason why NASA did not participate in the Giotto mission but was interested in a very advanced and complex sample return mission. In Europe the Solar System Working Group of ESA recommended a comet nucleus sample return (CNSR) mission in 1985, the year of the Giotto launch, as a follow up to the NASA CRAF (Comet Rendezvous Asteroid Flyby) mission based on the American Mariner Mark II spacecraft. When NASA cancelled their CRAF mission to comet 22P/Kopff because of budgetary issues, it became evident that the ambitious sample return mission was too expensive for ESA alone. Instead, ESA followed a similar concept and redesigned its Cornerstone mission as an asteroid flyby followed by

a comet rendezvous with in-situ examination, including two landing modules. But again NASA dropped out from the US/French lander project Champollion (Kerridge et al. 1997; Neugebauer and Bibring 1998) and finally one European lander (Philae) remained (Ulamec et al. 1997).

The new Rosetta mission was to replace the laboratory investigations of the returned sample by in situ analyses near the nucleus surface for an extended time (rendezvous) and direct contact using surface science packages (probes). The main science goals remained unchanged:

1. Determination of the global (mass, shape, volume) and dynamic properties (rotation state) of the nucleus
2. Determination of the nucleus physical properties and mineralogy
3. Investigation of the composition and origin of comets
4. Understanding and characterization of cometary activity and evolution

ESA's cornerstone mission was finally approved in November 1993, originally targeting comet 46P/Wirtanen, based on the Red Report SCI(93)7. The launch was scheduled for 2003 but could not be met because of technical problems with the launcher. Comet 67P/Churyumov–Gerasimenko, slightly larger than the original target, was chosen for a launch in 2004. The resources for the remaining surface science package (Philae) were increased by a factor two following the strong recommendation of the Rosetta Science Team. The finally proposed complex lander (with 10 instruments) with a mass of 100 kg comprised 40% of the science payload. For details of the mission and payload see Glassmeier et al. (2007).

4.2 The Journey

After the launch in 2004, two flybys at asteroids Šteins and Lutetia and in total four gravity assist maneuvers at Earth and Mars were conducted. The target comet 67P/Churyumov-Gerasimenko was reached in August 2014 (Accomazzo et al. 2016). The rendezvous lasted for more than 2 years and about 300 GB of data were collected by the eleven instruments and the navigation system of the spacecraft. The landing of Philae was scheduled for November 12, 2014 at a heliocentric distance 3 au. Due to a failure of the anchoring systems Philae bounced over the surface and came to rest in an initially unknown and unfavorable position (Biele et al. 2015). It was detected by the OSIRIS science camera only shortly before the end of the mission.

The observations of the nucleus of 67P by Rosetta started at a heliocentric distance beyond 3.5 au when activity was still mostly dormant. Rosetta followed the development of the activity through perihelion and terminated when the cometary activity had almost died again. The concept of the Rosetta rendezvous mission was best and uniquely suited to investigate the physical processes of activity.

4.3 What Have We Learned from Rosetta?

The objectives of points 2 and 3 (Sect. 4.1) would have been achieved by the original Rosetta CNSR mission by returning nucleus material into the laboratory. Now the composition of the nucleus had to be inferred from the analysis of the compounds found in the coma during the rendezvous. The success of this step strongly depends on the knowledge of the physical conditions and properties of the nucleus matrix material. The only way to derive these properties from the outside is the analysis of the physical processes on and near the surface that
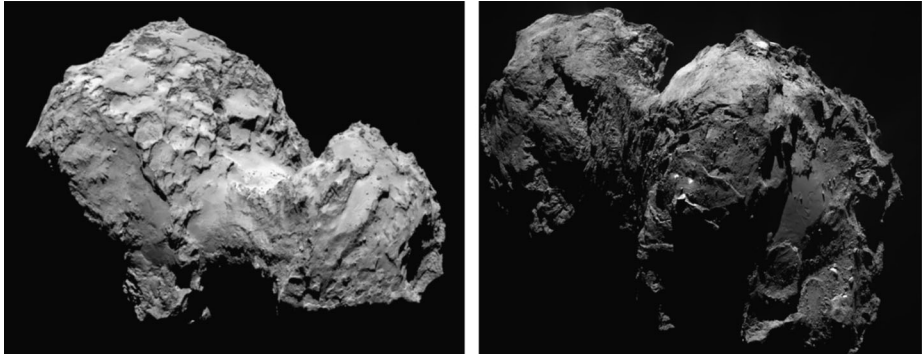
Fig. 2 The nucleus of comet 67P/Churyumov–Gerasimenko. Left: the north hemisphere is dust covered. Image taken pre-perihelion early in the mission. Right: the south hemisphere is very rough. Image taken after perihelion (images ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA)

Table 1 Global and dynamic properties of 67P

Property	Value			Remarks	Reference
Mass [kg]	$(9.982 \pm 3) \times 10^{12}$			before perihelion	Pätzold et al. (2019)
Mass loss [kg]	$(10.5 \pm 3.4) \times 10^{9}$			during orbit	Pätzold et al. (2019)
Volume [km³]	$18.56 \text{ km}^3 \pm 0.02$			before perihelion	Preusker et al. (2017)
Density [kg m⁻³]	537.8 ± 0.6			Ratio mass/vol.	see above values
Rotation period [h]	12.4043 ± 0.0007			before perihelion	Mottola et al. (2014)
	12.05506 ± 0.00002			after perihelion	Godard et al. (2017)
Tensor of inertia [kg m²]	9.3408457×10^{18}	5.6695663×10^{16}	0	see discussion in the reference	Kramer et al. (2019)
	5.6695663×10^{16}	1.6562414×10^{19}	0		
	0	0	1.8192083×10^{19}		

lead to activity and erosion. Here the surface science probe was most important (Goesmann et al. 2015; Wright et al. 2015). It is time to ask what have we learned from Rosetta with respect to the original goals of the mission.

4.3.1 Determination of the Global and Dynamic Properties of the Nucleus

The shape of 67P is unexpectedly complex. The nucleus seems to be composed from 2 rather evolved sub nuclei covered with pits, faults, cliffs, and mountains (see Fig. 2). The bigger of which looks like a strongly oblate sphere. The mass, volume, density, rotation axis orientation, rotation period, and moments of inertia of 67P could be determined to high accuracy by the extended rendezvous mission (Table 1).

The limited radar observations with a resolution in the m-range by CONSERT (Kofman et al. 2015) did not find any substantial voids, neither did the radio science instrument RSI (Pätzold et al. 2016). Considering the extremely low gravity on the nucleus surface a large scale tensile strength of the material of much less than 100 Pa (Groussin et al. 2019) is sufficient to support high cliffs (Hathor) and overhangs (Groussin et al. 2015; Attree et al. 2018). It turns out that the material strength to gravity ratio on the comet is quite similar to the equivalent on earth. It is therefore not surprising that the eroded nucleus surface on many places looks earth-like.

The geology of the surface is quite diverse, about 60 different regions could be discerned (Thomas et al. 2018) with rocky consolidated nucleus matrix material, very rough, boulder covered, with steep cliffs and huge cliff walls on one hemisphere and dust covered with pits, terraces, spires, and flats that seemed to be covered by thick layers of back fall material on the other hemisphere. All types of surface morphologies observed on the nuclei previously passed by flyby missions can be found on comet 67P (El-Maarry et al. 2019). This strongly suggests that at least the normal JFC are alike and their surfaces reflect different states of evolution with morphologies that depend on orbit, shape, and rotation of the individual comet nucleus.

The strong dichotomy between the northern regolith covered surface and the consolidated "rocky" southern hemisphere (Fig. 2) demonstrates that it is almost impossible to draw conclusions about the composition and physical processes of individual nuclei from remote sensing observations, from Earth orbit, or even from flybys. Many observations and conclusions of the past have to be reassessed.

Less suggestive is the indication of onion shell-like structures of both lobes separately (Massironi et al. 2015). If true, it would confirm that the bilobate shape was formed by the merger of two bodies rather than by erosion (Jutzi and Asphaug 2015; Vavilov et al. 2019). No differences of the physical and chemical properties of the bodies were found.

The surface color of 67P is rather uniformly red. VIRTIS detected water ice mainly as frost right after local sunrise (De Sanctis et al. 2015). While this frost is only short lived more and more icy patches were found when the comet approached perihelion. Based on mutual observations less red ("blue") bright patches were observed by OSIRIS and interpreted as water ice. The lifetime of some lasted weeks and months. Overall the surface color changed from red towards blue while the comet became more and more active (Fornasier et al. 2016). The trend reversed after perihelion; a strong indication that the surface properties systematically changed. How this influences the activity remains an open question.

Changes of the spin state were measured with high accuracy and interpreted in terms of non-gravitational forces caused by cometary activity (Keller et al. 2015b; Kramer et al. 2019).

4.3.2 Determination of the Nucleus Physical Properties and Mineralogy

VIRTIS measurements revealed that the surface of the comet is characterized by a dark refractory polyaromatic carbonaceous component mixed with opaque minerals (Quirico et al. 2016). VIRTIS data do not provide direct insights into the nature of these opaque minerals but they may consist of Fe-Ni alloys and FeS sulfides. A semi-volatile component, consisting of a complex mix of low weight molecular species is likely a major carrier of the 3.2 μm band (Quirico et al. 2016). Water ice significantly contributes to this feature in the neck region but not in other regions of the comet. COOH in carboxylic acids is the only chemical group that encompasses the broad width of this feature.

Both lobes are similar and in fact the whole nucleus is homogeneous at a meter-scale (Herique et al. 2016). The density of the nucleus of 538 kg/m^3 confirmed previous

strongly model dependent estimates based on the effect of non-gravitational forces (NGF) on cometary orbits (e.g. Rickman et al. 1987; Davidsson and Gutiérrez 2005). This leads to an overall porosity between 50 and 80%.

VIRTIS found the thermal inertia to be $< 170\,\mathrm{J\,K^{-1}\,m^{-2}\,s^{-0.5}}$ (Marshall et al. 2018), or even $< 50\,\mathrm{J\,K^{-1}\,m^{-2}\,s^{-0.5}}$ in most regions (Tosi et al. 2019). This is consistent with a highly porous structure.

The unclear environmental circumstances of Philae during its short observation campaign question the reliability of the measurements (Böhnhardt et al. 2017). The few high resolution images (Bibring et al. 2015; Mottola et al. 2015; Schröder et al. 2017), the SESAME experiment (Möhlmann et al. 2018; Knapmeyer et al. 2018) and the MUPUS penetrator (Spohn et al. 2015) provided limited information on the mechanical properties of the surface. Material parameters (tensile and compressive strength) were as well derived from modelling the impacts during the touch downs (Biele et al. 2015; Heinisch et al. 2019). The resulting material properties are quite controversial and difficult to reconcile with the very low values derived from the observations of cliff collapses and morphological structures such as overhangs.

The dust to ice ratio in cometary nuclei has been of particular interest since it turned out that the nucleus matrix is dominated by refractories and not by ice (Keller 1989). Ground based observations of comets reveal dusty and gaseous comets indicating a wide range of this ratio. However, the determination of the dust amounts is rather uncertain because large particles (carrying most of the mass) cannot be observed in the visible wavelength range. Even after the rendezvous the intrinsic refractory to ice ratio of 67P remains puzzling since a direct measurement is missing and derived values are strongly model dependent (see Choukroun et al. 2020, this issue).

The potential for erosion by water ice sublimation is 4 times higher for the southern than for the northern hemisphere (Keller et al. 2017). Therefore, if more than 25% of the dust liberated on the south falls back on the north it will accumulate there from orbit to orbit. Seasonal variations of the cover by back fall were observed at several places particularly at northern mid latitudes. The thickness of the cover was estimated to 0.5 to 1 m (Hu et al. 2017). A more precise measure of 1.4 m could be derived for the variation of the ground level at Hapi using the height of outcrops (Cambianica et al. 2020). How these relatively large erosion values from the area with the least overall solar insolation can be conciliated with a total loss of less than 0.5 m averaged over the whole surface (Keller et al. 2017; Pätzold et al. 2019) remains a puzzle.

About half of the total mass loss of the nucleus of 67P determined by RSI (Pätzold et al. 2019) is attributed to the integrated gas production (Biver et al. 2019; Läuter et al. 2019). This results in a dust to gas ratio in the coma of about 0.6 to 1.5 (Choukroun et al. 2020, this issue). How this does correlate with the dust to ice ration in the nucleus is under debate. A large amount of refractories were ejected in the centimeter and decimeter size range (Fulle et al. 2016; Ott et al. 2017). A sizable percentage fell back on the then inactive northern hemisphere and possibly accumulated there from orbit to orbit. The dust chunks are "wet", contain water ice (but no super volatiles) that then sublimes from the northern hemisphere. The water driven activity may not be strong enough to remove all the dust. Activity on the northern hemisphere could still be maintained from orbit to orbit by a cover of fresh material transferred during perihelion from the south. In this scenario the dust to gas mass ratio derived from the loss of material does not reflect the dust to ice ratio of the original cometary material. The erosion is controlled by super volatiles on the southern hemisphere and not by water ice sublimation. The overall erosion of the cometary surface (mainly on the south) would be much stronger than estimated from the total mass loss. A varying amount

Fig. 3 The production rates of H_2O, CO_2, CO, and O_2 of 67P as function of heliocentric distance (Läuter et al. 2019)
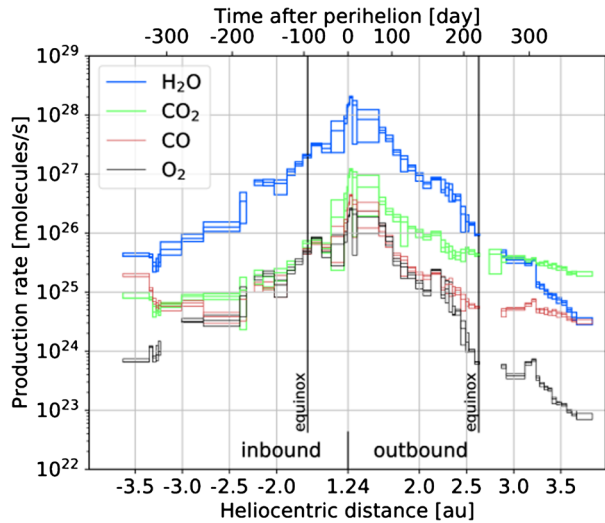
of back fall material controls the varying observed dust to gas ratios in the coma and tail of comets that could still have similar intrinsic dust/ice ratios.

4.3.3 Investigation of Composition and Origin of Comets

The long term observations during the 2 years of rendezvous produced an abundance of compositional data. However, the seasonal mass transfer not only influences the observed dust to ice ratio and morphology of the surface but it also causes a seasonal and spatial variation of gas compounds in the near nucleus coma what makes an interpretation difficult. This is particularly obvious for the CO_2 to H_2O ratio (Läuter et al. 2019) if one compares the pre-perihelion to the post-perihelion ratios. The ratio changes from about 5% before perihelion to more than 100% later during the rendezvous (Fig. 3). CO behaves similarly. Stochastic, time limited, observations of the ratios of super volatiles to water are not conclusive for the intrinsic ratios. This also explains why no correlation of these ratios with cometary type (JFC, Oort cloud) and possibly with evolutionary age or place of origin was found (A'Hearn et al. 2012). One of the key results of the rendezvous mission Rosetta is that time limited incidental observations of the coma composition do not necessarily reflect the intrinsic composition of the nucleus, neither in the content of volatiles nor in the refractory to volatile ratio. The summary given by Delsemme (1982) in the Comets book that cometary nuclei are alike and homogeneous still holds.

ROSINA took advantage of the long measuring cycles and approximately doubled the number of detected compounds found in the coma. These include aromatic ring compounds as well as long chain hydrocarbons which can be linked to gas phase and grain surface chemistry in dark molecular clouds (Hasegawa et al. 1992). Larger molecules beyond mass 60 are inferred by the IR VIRTIS observations (Capaccioni et al. 2015) but do not sublime easily. Correlating the cometary abundance ratios with those observed in the ISM suggest formation under similar circumstances. Comparable results were first derived for comet C/1995 O1 (Hale–Bopp) (Bockelée-Morvan et al. 2000). The large number of sulfur species (H_2S, S_2 etc.) provide a further hint of molecular cloud chemistry on dust grains (Calmonte et al. 2016).

ROSINA confirmed that the various highly volatile compounds (N_2, CO, Ar, Xe, etc.) require the formation of nuclei at a temperature below 25 K and that they were never warmed up, i.e. as part of a large body by radiogenic heating (Rubin et al. 2015). This was already concluded after the comet Halley flybys (Altwegg et al. 1999). Surprising was the finding of the highly volatile and reactive molecule O_2 in the percentage range well correlated with H_2O, not with CO_2 like most other highly volatile species. Its formation process is unclear but points to an interstellar origin.

The extended observations of ROSINA yielded a large number of isotope ratios. The observed D/H ratio of 1.5×10^{-5} is much higher than found in any other comet. The variability of this ratio from comet to comet indicates that the various comet classes (JFC, Oort cloud) originate from the same extended reservoir but undergo different dynamical evolutions (Altwegg et al. 2015). This confirms the earlier conclusions derived from varying CO_2 and CO ratios relative to water for a variety of comets (A'Hearn et al. 2012).

Their homogeneity, their low density and tensile strength may suggest that comets are formed by accretion of a collapsing cloud (streaming instability) of pebbles (Blum et al. 2014; Davidsson et al. 2016). However, using the same Rosetta data basis different authors come to different conclusions about the importance and effects of impacts in the early history of comets (comp. Rickman et al. 2015; Davidsson et al. 2016).

The confirmation of the amino acid glycine (Altwegg et al. 2016) could be a hint that comets may have brought ingredients of life to Earth in an early phase of the Late Heavy Bombardment (LHB) but this remains speculative and is not at all proved.

Results from ROSINA considerably strengthen the non (pre) solar origin of some cometary compounds. Isotope ratios of Xe, Si, S, and H as well as the presence of highly volatile compounds such as S_2 and the correlation of O_2 with H_2O require pre solar ice. Comets are formed at low temperature and contain original interstellar material and compounds processed in the inner solar system (see also the Deep Space results A'Hearn 2006) but mixing of proto solar/proto planetary nebula material was inefficient.

The very high D/H ratio compared to that of Earth rules out that comets of 67P type played an important role in delivering water to Earth. The abundance ratios of various deuterated water molecule suggested that water was inherited from the pre solar cloud (Furuya et al. 2016). Overall the observed isotope ratios are not consistent, some ratios are enhanced relative to the solar value, some are depleted (Hässig et al. 2015; Calmonte et al. 2016; Rubin et al. 2017). Of particular interest are the Xe isotopes that seemed to have been trapped in the cometary ice before the solar system formed. Their ratios match that of the unknown source of U-Xenon in the Earth's atmosphere (Marty et al. 2017).

4.3.4 Understanding and Characterizing Cometary Activity and Evolution

The determination of the dust to ice ratio from coma and tail observations is difficult (see Sect. 4.3.2) and the dust to ice mass ratio was long underestimated and considered to be less than one. The predominance of the refractory material was inferred from results of the Giotto mission and confirmed by observations of cometary trails that consist mainly out of centimeter to decimeter particles (Sykes and Walker 1992). Whipple (1950) assumed that large dust particles (meteoritic material) form a mantle on the surface if they cannot be removed by the subliming ice. The particles do not interact and are retained by the gravity of the nucleus. Kührt and Keller (1994) showed that mantles of loose grains are stabilized by van der Waals forces that are high enough to withstand the gas pressure. This would lead to a growing permanent dust mantle and was the starting point of the "activity paradox" in the literature (Blum et al. 2014; Vincent et al. 2019): how can a comet stay active when such an

insulating mantle is formed on its surface? Rosetta was supposed to disentangle the physical processes of activity.

The rendezvous mission did bring the complexity of activity and erosion processes of cometary nuclei to our attention. It revealed that mass transfer by back fall material is important for our understanding and interpretation of cometary appearances and as a consequence will lead to re-assessment of many earlier papers and conclusions. This could well be one of the most significant results of the mission. This complexity was mainly triggered by the strong obliquity of the rotation axis of 52° that causes pronounced seasons on the nucleus. Their impact was enhanced by the near coincidence of the southern solstice with the perihelion passage resulting in a short (< 1 y) but intense southern summer while the northern summer lasts for the rest of the orbit. Rosetta approached the comet during northern summer when the southern hemisphere was not illuminated. This imbalance of the seasons produces a remarkable dichotomy in the morphologies of the hemispheres. The northern hemisphere is in large parts covered by grained material that fell back when the southern hemisphere was strongly active. The south shows mostly the consolidated nucleus matrix and is very rough.

The dark surface produces dust activity whenever and wherever the sun shines. The strength of the gas activity is variable within an order of magnitude (Kramer et al. 2019). A correlation with surface morphology could not be established. Some dust features can be traced to specific areas on the nucleus, and result conceivably from locally enhanced outgassing and/or dust emission (Shi et al. 2018). Linking observed coma morphology to the distribution of activity on the nucleus remains difficult.

It has not been possible to discern active from inactive surfaces, neither by remote sensing nor by the in situ coma measurements. This is not astonishing because from a distance of 10 nucleus radii ($\sim$20 km) the whole surface contributes to the signals observed by instruments measuring coma compounds, the nucleus behaves like a point source (Rezac et al. 2019). Unfortunately the dust near the nucleus could only be observed on the limb or against shadowed areas but not directly at the source. Only little amounts of CO_2 originate from the northern dust covered surface. The regolith is depleted in CO_2 relative to water.

4.4 What Do We Miss?

Rosetta provided an unprecedented wealth and detail of data (about 300 GB) of the cometary nucleus of 67P. We followed the comet evolution along its orbit through perihelion. We determined the global properties of the body, observed activity and erosion, detected many more compounds in the coma. But some basic questions remain unanswered.

We did not properly characterize the physical properties of the matrix material, mainly because the lander Philae failed to provide reliable data. From ROLIS image we can conclude that the pores at the surface are smaller than the resolution limit of 0.8 mm (Schröder et al. 2017). Recent models cover the range from submicron, e.g. (Keller et al. 2015a; Skorov et al. 2017) to cm (Gundlach et al. 2015) pores. The strength at small scales and the distribution of ice and dust below the surface were not measured. The derived thermal inertia of the surface from VIRTIS and MIRO data is not detailed enough to calculate the heat transport through the upper layers. For this, one needs the depth- and temperature-dependent heat conduction coefficient that could not be measured by MUPUS since the thermal sensors were not hammered into the ground as planned (Spohn et al. 2015). Consequently, modeling work of the temperature profile and the activity behavior is limited since its outcome strongly depends on these unconstrained parameters (Prialnik et al. 2008).

Little was found beyond the results from the 1P/Halley flybys about the semi- or non-volatile hydrocarbon components that constitute probably the majority of the refractories

(Wright et al. 2015). The mineral components are compatible with a mixture of silicates and fine-grained opaque compounds, including Fe-sulfides like troilite and pyrrhotite. The organics contain COOH and OH-groups and a refractory macromolecular material bearing aliphatic and polycyclic aromatic hydrocarbons (Filacchione et al. 2019). A more detailed composition of the refractories and organics remains puzzling (Quirico et al. 2016).

Icy patches and frost were observed but no criteria could be established that would allow to characterize the strength of activity, or even any inactivity of surface regions. Systematic measurement of local surface temperature variations as function of insolation and illumination geometry in good resolution as an indicator of sublimation processes are missing.

Unfortunately, the orbit parameters of 67P were not determined by ESA. Just the trajectory of the spacecraft was evaluated based on piece wise approximations. As a consequence the acceleration of the nucleus caused by its activity cannot be derived. This forfeits the unique chance to model the non-gravitational forces (NGF) for a nucleus with well-known mass, shape, and rotation parameters. The attempt by Kramer and Läuter (2019) to overcome this shortcoming by approximation of the perturbed cometary orbit does not constrain parameters well enough.

Although new details of cometary activity are identified such as active pits with lateral sublimation from their walls, cliff collapses, and night/day terminator region activity (see Vincent et al. 2015; Pajola et al. 2017), the more descriptive than analytic observations and measurements of Rosetta do not provide the information required to understand cometary activity in more detail.

4.5 Why Did We Not Make a Real Breakthrough in Understanding Activity?

A breakthrough could not be achieved in respect to the important goal of understanding cometary inactivity in detail. We still do not know how the interplay of dust and gas near the surface takes place, which role water and super volatiles play for the activity, or how outbursts are triggered. The lack of knowledge of the microphysical parameters and processes prevent realistic modelling of the dust ejection.

Why did that happen?

The spacecraft was not near the nucleus when activity dominated. We did not see where and how frequently large particles in the centimeter and decimeter or even meter size range were lifted although the limiting resolution of the camera was easily sufficient. In the active phase of the comet the spacecraft was hundreds of kilometers away. The relatively long legs of the hyperbolic spacecraft trajectories did not provide enough control for systematic local observations. As a consequence the lift-off mechanisms of the dust of different sizes remain unresolved. Furthermore, this is one of the reasons that the essential refractory to volatile (ice) ratio of the nucleus matrix is not well constrained.

Rosetta's many close flybys were still only flybys and made it difficult to impossible to achieve systematic observations of specific points of interest and of particular activities. Just to give an example. Very early in the mission a long and wide fracture along the Aswan cliff was observed. Talus on its bottom showed that break offs or collapses had taken place in the past. So it was anticipated that here a collapse was imminent and could take place during this perihelion passage. The collapse took place resulting in a dust cloud activity that was serendipitously observed by the navigation camera (Pajola et al. 2017). It took 5 days to confirm the collapse but more than three months to look again at the cliff with somewhat better resolution and improved illumination conditions. It took more than a year before high resolution images of the cliff wall were taken. Of course we missed all the information that could have been derived from the fresh surface revealing the nucleus interior immediately after the collapse.
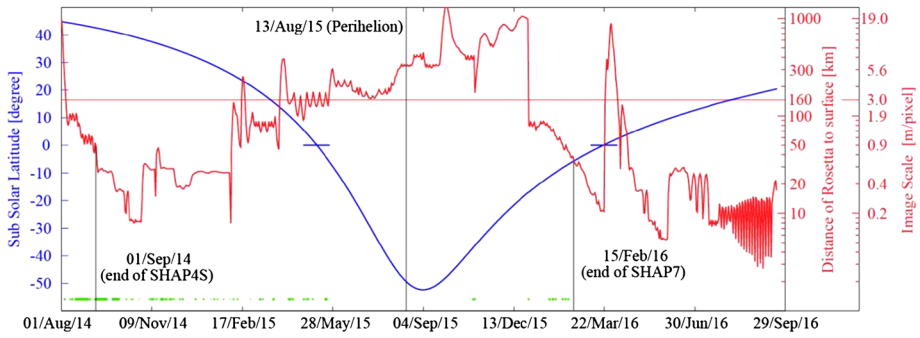
Fig. 4 Distance of the Rosetta spacecraft relative to the nucleus of 67P and image scale of the NAC OSIRIS camera on the right ordinates (red curve) and the sub solar latitude on the left ordinate (blue curve), green dots indicate images used for shape modelling (Preusker et al. 2017). Abscissa shows the date. Time of perihelion is indicated

The limitations of the spacecraft star trackers to operate in the dust environment near the nucleus strongly hampered the analysis of the activity processes. The design concept of the spacecraft safety rules (adapted from missions around planets) turned out at least as disadvantageous. They required Rosetta to stay on hyperbolic orbits or on stable closed orbits. This made systematic and repeated observations of points of interest difficult or impossible. In addition, much time was wasted (for most instruments) far away from the comet nucleus at the return points of the hyperbolic arcs. The very low escape velocity (1 m/s) from the nucleus of 67P would allow the spacecraft to hover above it and to move towards the Sun in case of emergency (safe mode). This concept was unfortunately rejected during the design phase of the Rosetta spacecraft. Operational turnaround times at the beginning of the mission in the order of months, later still one or two weeks prevented any fast reaction to activity events.

A further big shortcoming was that the beta angle (angle between the direction towards the sun and the orbital plane of the spacecraft) had to be $> 60°$. This induced navigation requirement led to solar incident angles of more than 60°, not at all optimal for mapping and surface observations such as temperature determinations. Even much less favorable were the terminator orbits of the spacecraft. Interpretation of images for phase angles close to or beyond 90° is difficult and quantitatively ambiguous, never mind that a major part of the images is taken up by black shadows. Of course here systematic repetitive observations are possible but they take place above the least illuminated and hence least active surface. In addition, the active hemisphere on one side and the dark inactive hemisphere on the other side make modeling the local coma difficult and uncertain.

Figure 4 shows that the spacecraft spent less than 20% of the rendezvous interval at a distance below 10 nucleus radii (< 20 km) and this only during times of low activity levels of the comet at large heliocentric distances. This is too far off the surface for the instruments to map the chemical homogeneity of the morphological regions by in situ measurements of compounds found in the coma. Beyond 20 km the nucleus behaves essentially like a point source. This holds for the in situ density measurements of ROSINA as well as for the remote sensing instruments such as VIRTIS and MIRO (Rezac et al. 2019). Originally it was envisaged to reach distances as close as one nucleus radius above the surface (< 2 km) and map most of the surface with a resolution < 10 cm/px (Schwehm and Schulz 1999).

The high phase angles of the surface observations complicated measurements of the temperature but also of other radiative properties of the surface. As discussed earlier the derived

(not directly measured by VIRTIS) surface temperatures were not accurate enough to constrain the thermal properties of the surface that would be important for activity. The interpretation of the MIRO temperature data depends on the little constrained material properties and their homogeneity.

The top level answer to why we missed a breakthrough is that the spacecraft performance and its operation did not allow the instruments to be used to their capabilities and in a systematic way. One could characterize the Rosetta mission as a series of flybys interrupted by bound orbits in the least optimal configuration along the terminator.

In summary, a breakthrough in our understanding of comets requires the understanding of cometary activity processes. Only then meaningful models can convert the observations of the coma composition and phenomena into knowledge about the nucleus composition and its structure.

5 Lessons to Be Learned for Future Cometary Missions

ESA did not discuss the important lessons learned report within the science community after the end of the Rosetta mission. We therefore summarize our points of view.

As discussed before, major progress could be achieved in the detection and measurement of chemical and isotopic compounds of the comet, in plasma physics (Goetz et al. 2016; Mandt et al. 2016) but not in understanding how activity works. Basic deficiencies of the mission stem from its early stages when the science objectives were discussed and the spacecraft and mission were designed. What are the shortcomings and what can be done better in the future?

1. The science goals were not precisely enough defined that they could be used as compelling design and performance criteria and finally as success criteria. In fact success criteria were not defined. Debilitating was also the heritage from the originally conceived CNSR. The Red Report (SCI(93)7) intended to demonstrate that most of the original science goals of the CNSR mission could still be achieved by the rendezvous concept, rather than concentrating on the physical processes of activity that could uniquely be investigated by the rendezvous.
2. The in situ chemical analysis of coma compounds was presented as a surrogate for the laboratory investigations of a nucleus sample. It was not realized that a comprehensive coma analysis still requires the knowledge of how to draw conclusions on the composition and physics of the nucleus itself. This also holds true for deriving the refractory/ice ratio in the nucleus and of outgassing rates from coma measurements.
3. A major deficiency of the science payload on Rosetta was the absence of a thermal IR instrument that could provide the surface temperatures with adequate spatial resolution and accuracy over a temperature range from < 100 to > 350 K. Temperature variations are most analytic for subliming ice, even under the surface and even when intimate dust/ice mixtures mask the ice bands in spectra (Yoldi et al. 2017). Omitting the proposed thermal mapper ("Thema") was probably also a consequence of the imbalance of the science goals.
4. The over-complexity of the Philae lander loaded with sophisticated in situ analysis instruments investigating chemical aspects is also a consequence of the desire to achieve laboratory like investigations at the comet. Early in the mission design two surface packages were discussed, adequate for a completely unknown environment with all its risks (Kührt et al. 1997). Simple clam shell like probes were proposed that operated on

batteries and concentrated on the physical properties like tensile strength and porosity applying high resolution imaging. Two packages were suggested to mitigate the risk and to probe the diversity of the surface (Kerridge et al. 1997; Ulamec et al. 1997). Leaving the design concept and science criteria in the hands of a PI and his coinvestigators (Wittmann et al. 1999) resulted in a too ambitious concept of the lander without adequate funding and spacecraft resources. A major part of the science payload (40% by mass) was not under the control of ESA. The advertised capabilities made this instrument so important to the mission that the PI lander became mission critical and significantly influenced the operation of Rosetta over many months, not only before the release of Philae but also afterwards during the desperate attempts to re-establish contact and even by the search for the dead lander (Ashman et al. 2016).

5. An important design limitation for instruments is the maximum data rate and total data budget. It is not helpful to created data that cannot be transmitted to earth. The envisaged budget for Rosetta during the design phase was more than an order of magnitude smaller than what was finally achieved. For instance a camera with longer focal length that could have achieved images of similar quality as the NAC from larger distances would have been very useful and reasonable. This often practiced conservatism in the announced resources, particularly in the present extreme, leads to sub optimal instrument design and performance.

6. Two significant deficiencies of the spacecraft design had the strongest impact on the success of the Rosetta mission. The dust environment in the near nucleus coma was not a surprise. Actually, the dust production during the Rosetta apparition of 67P closely followed the amounts observed during earlier orbits (Snodgrass et al. 2017). The impact of the dust particles on the performance of the star trackers was not realized before arrival at the comet and little was done to mitigate the problem (Accomazzo et al. 2017). This led to distances from the comet during the peak of activity about a factor 100 beyond what was anticipated during the design phase with all its consequences for the resolution of the instruments.

7. An even worse influence on the success of the mission resulted from the fact that the spacecraft could not hover near the nucleus but had to move on hyperbolic or bound orbits to avoid the risk of crashing into the nucleus in case of malfunctioning. This made mapping difficult and systematic observations almost impossible. One can characterize the Rosetta mission as a series of flybys interrupted by bound orbits mostly in the least optimal configuration along the terminator. This complex scheme posed a major challenge for the operational team requiring a huge effort that was skillfully mastered, but it was definitely not optimal or even adequate for science.

8. The situation was aggravated by the requirement that the minimum beta angle had to be > 60°, required by navigation constraints. This restricted measurements of the optical properties and mapping of the surface. In addition, eclipse or near eclipse observations would have been very helpful to derive dust grain properties and size distribution.

9. The spacecraft and instruments operation software, specifically developed for Rosetta, was late, too late to be finished in time, and had to be replaced by an adaptation of existing software developed for multiple missions (MAPPS). The foreseen time during hibernation (31 months) was not sufficient for the development and implementation. Early warnings based on experience with the Cassini–Huygens mission were disregarded.

10. The operation of the science instruments had turnaround times of about one month at the beginning of the mission. Again, the spacecraft operation was very conservative and science requirements were not given proper attention during the operational phase. At the end of the mission celebrating a PR event for the final crash of the spacecraft on the

surface was more important than to take risks to finally meet the originally promised near surface observations at good lighting conditions.

11. A continuous effective leadership to coordinate and optimize the science operations and data transfer rates for all instruments according to the scientific goals of the mission is the prerequisite to achieve maximum scientific return from a complex planetary mission like Rosetta. ESA decided to replace the Rosetta Project Scientist, a comet observer, by a plasma physicist after the spacecraft came out of hibernation in 2013, about a year before the comet rendezvous started. In addition, the ESA mission manager, a cometary scientist already involved in the Giotto mission, was also replaced. The deprivation of comet science expertise and the lack of a clear strategy how to meet the scientific requirements (see #10) led to suboptimal mission planning at the target where safety aspects always dominated but coordination and promotion of cometary science goals did not receive the required attention. In addition, the organization and leadership of the Rosetta Science Working Team was weak and hence not focused.

It is clear that no mission design and performance is perfect, but Rosetta shows more than the usual deficiencies many of which could have been avoided by better planning this cornerstone mission. The long travel time of 10 years was not adequately used.

6 Summary and Outlook

The Rosetta mission, staying over two years with comet 67P, has dramatically kindled the interest in cometary physics in the science community but also in the public. The harvest of the mission results is not over yet and further progress will be achieved. It can be expected that many of the previous comet observations and models will be reassessed in the light of the very detailed and copious measurements of comet 67P by Rosetta.

6.1 Flybys Versus Rendezvous

A comparison between the programs of both agencies, ESA and NASA, suggests itself. The total cost of the three American small missions with five flybys and the Rosetta cornerstone mission seem to be comparable. Rosetta could follow the evolution of cometary activity from its onset through perihelion and revealed the importance of seasons for the nucleus evolution. On one hand the interpretation of the extensive Rosetta campaign with its long term observations of the complete surface is more involved and more significant for the understanding of comets as members of the solar system and their early formation. On the other hand many inferred results achieved in the brink of the short flybys can now be considered consolidated. The detailed observations during the Rosetta rendezvous suggest that the apparent diversity of the admittedly still small number of "typical" JFC comets can be understood as the expression of cometary nucleus evolution in the inner solar system. Their diverse morphology is caused by their specific orbit parameters, rotation, shape, and seasonal effects of the more complex than previously modeled cometary activity. The question which of the programs—several flybys or the single extended rendezvous—provided more and/or better results is certainly legitimate from the agency and science political points of view but is difficult to assess objectively. It is, however, obvious that the diverse flybys are a very good and important complement to the detailed results of the Rosetta mission for one single comet. But it is also true that Rosetta yielded results that cannot be achieved by a flyby mission.

6.2 Major Scientific Conclusions from Rosetta

1. Time limited incidental observations of the coma composition do not necessarily reflect the intrinsic composition of the nucleus, neither in the content of volatiles nor in the refractory to volatile ratio. Mass transfer by back fall material is important for our understanding and interpretation of cometary appearances. This insight will lead to a reassessment of many papers that discuss cometary composition and its temporal and/or spatial variation or compare the global composition of specific comets. It is obviously difficult to prove that comets are intrinsically different.

2. The detailed observations of the surface revealed that most morphologies have already been found on nuclei passed by flybys. This strongly suggests that all (so far visited) comets are alike. The diverse morphologies are hence an expression of evolution.

3. Hydrocarbons, semi volatile or refractory compounds, contribute a major, if not the major, fraction of the mass of the nucleus. Rosetta observations confirmed their importance.

4. Findings of the mass spectrometry strongly suggest that the formation of the comet took place at very low temperatures (< 25 K) and a considerable part of its molecules is of interstellar origin.

5. Isotopic investigation based on ROSINA data suggest that comets significantly contributed to the inert gases in the Earth atmosphere but not to the terrestrial water.

6. A new paradigm for cometary activity seems to emerge. The activity and erosion is controlled by super volatiles (CO_2, CO), more than by water ice sublimation. The overall erosion of the cometary surface (mainly on the south in the case of 67P) is stronger than estimated from the total observed mass loss. Varying amounts of back fall material control the observed dust to gas ratios (smaller than the refractory to ice ratio) in the coma and tail of comets. The background (continuous) dust activity is driven mainly by H_2O that does not remove all dust on the northern hemisphere during northern summer—in fact may not be able to maintain cometary activity. Desiccated dust accumulates on the north but notwithstanding the overall activity stays constant because the north is reactivated every orbit by wet back fall.

6.3 Major Open Points Remain

1. The composition measurements continue to indicate that comets carry material of interstellar/pre solar origin as well as solar processed compounds. Many more details were revealed but no clear concept has surfaced yet.

2. The existence and importance of amorphous water ice in the nucleus is still an open question.

3. Rosetta data are not conclusive concerning the collisional environment during the formation of the comet and right afterwards. This point is important to constrain evolution models of our planetary system such as the Nice model.

4. The refractory to ice ratio in cometary nuclei has been of particular interest since it constrains comet formation models in the solar nebula. However, it may differ from the dust/gas ratio in the coma and Rosetta did not provide reliable values for both.

5. Physical parameters such as the microstructure and small-scale strength of the surface layer are essential for the modeling and understanding of the physics of activity processes. Here Rosetta could not reach a breakthrough caused by the overall concept (one lander only) and the failure of Philae at a couple of essential measurements.

6. Very limited progress was made in revealing the physical processes of activity, both of the "normal" background activity and of the frequent outbursts. We did not see where

and how the frequent large particles in the centimeter and decimeter or even meter size range were lifted off.

7. Modelling the effects of the non-gravitational forces on the orbit provides additional constraint for the physical parameters of the nucleus. These model calculations based on the well-known properties of a nucleus would be highly desirable to calibrate the estimates for a large number of observed comets. Unfortunately, the orbit parameters of 67P have not been determined to the required accuracy.

Without any doubt Rosetta was a milestone in cometary research. It provided 300 GB of data that have only partly been analyzed up to date. Many new findings have been published in recent years. However, key questions have remained unanswered. Future rendezvous missions should optimize the operational scheme and bring original samples back to Earth (Thomas et al. 2019). Mission proposals such as CAESAR (NASA) that intends to visit 67P again and bring back samples (not selected), Comet Interceptor (ESA) to a dynamically new comet (selected www.cometinterceptor.space), the Japanese Destiny+ mission passing 3200 Phaeton (Kawakatsu and Iwata 2013), and a Chinese Asteroid Sample Return concept with an additional rendezvous of a main belt comet (see http://www.cnsa.gov.cn/english/n6465652/n6465653/c6805893/content.html?from=singlemessage&isappinstalled=0) are already in a selection process and could close the gap of open questions.

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