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The refractory-to-ice mass ratio in comets

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ABSTRACT

We review the complex relationship between the dust-to-gas mass ratio usually estimated in the material lost by comets, and the refractory-to-ice mass ratio inside the nucleus, which constrains the origin of comets. Such a relationship is dominated by the mass transfer from the perihelion erosion to fallout over most of the nucleus surface. This makes the refractory-to-ice mass ratio inside the nucleus up to 10 times larger than the dust-to-gas mass ratio in the lost material, because the lost material is missing most of the refractories which were inside the pristine nucleus before the erosion. We review the refractory-to-ice mass ratios available for the comet nuclei visited by space missions, and for the Kuiper Belt Objects with well-defined bulk density, finding the 1-σ lower limit of 3. Therefore, comets and KBOs may have less water than CI-chondrites, as predicted by models of comet formation by the gravitational collapse of cm-sized pebbles driven by streaming instabilities in the protoplanetary disc.

Key words: space vehicles – comets: general – comets: individual: 67P/Churyumov–Gerasimenko – Kuiper belt: general – protoplanetary discs.

1 INTRODUCTION

The refractory-to-ice mass ratio in comets is a key constraint to models of the origin of comets, and of the radial distribution of water and ices in the protoplanetary disc. Ground-based observations and past flybys to comets have provided estimates of the dust-to-gas mass ratio of many comets (Fulle 2004; Sykes et al. 2004). The dust size distribution inferred in all comets implies that the ejected dust mass is dominated by the largest ejected chunks, the mass of which could not be evaluated until the EPOXI's flyby at comet 103P/Hartley 2 (103P hereinafter) (Kelley et al. 2013, 2015). It follows that all the past estimates of the dust-to-gas ratio may be lower limits, when the largest ejected dust was assumed to be smaller than the chunks observed in 103P and 67P/Churyumov-Gerasimenko (67P hereinafter).

In general, dust is a mixture of refractories and ice, with fractions depending, e.g. on the dust size. Gas in cometary comae results from the sublimation of ice present just below the nucleus surface and in the ejected dust (distributed sources). Here, we aim to discuss the relationship between the refractory-to-ice mass ratio inside the nucleus and the dust-to-gas mass ratio quoted above, which is a complex issue. For instance, the fact that dust comes from the nucleus surface, much drier than the nucleus interior, does not imply that the refractory-to-ice mass ratio inside the nucleus is lower than the dust-to-gas ratio in the lost material, if the dust fallout is dominated by refractories. Nucleus refractories are a mixture of minerals (mainly sulphides and silicates) and organics, i.e. hydrocarbons.

Here, we review all the processes observed at the 67P nucleus surface, allowing us to infer the refractory-to-ice mass ratio inside the 67P nucleus according to the available literature. In particular, in Section 2.1, we review all available results concerning the dust loss rate at perihelion, which is by far the largest one during the 67P orbit, eroding the nucleus of meters, thus exposing pristine material. However, it turns out to be inconsistent with the measured mass lost by the nucleus during every orbit. The only way to reconcile these two results is by taking into account the dust fallout, which is introduced in Section 2.2. In Section 2.3, we review all available data regarding the water loss during perihelion, which has been measured at different rates according to the observing technique, possibly due to distributed water sources, still at an unknown level (thus parametrized by two extreme end-cases). The

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main outcomes of these first three subsections are summarized in short statements, which are the summary of what discussed in each subsection, and which are referred to in the following subsections to infer scenarios coherent with all the reviewed results. In Section 2.4, we consider the mass balance among dust loss, water loss (both from the nucleus and distributed sources) and fallout, showing which refractory-to-ice mass ratios inside 67P are consistent with all the data and parameters discussed in the previous subsections, and with the dust-to-gas mass ratio measured in the lost material. These results constrain the fallout mass and the dominant fallout processes (Section 2.5). Then, we check if these results are consistent with the available structural models of 67P (Section 2.6), with the measured dielectric permittivity (Section 2.7), and with the possible constraints coming from outbursts and landslides (Section 2.8). All these subsections are then summarized in Section 2.9, where we also discuss the thickness of the wet deposits accumulating every orbit mainly on the northern hemisphere. In the following sections, we discuss the implications for other comets, and compare the results to other objects of the outer Solar system.

2 ROSETTA AT 67P

2.1 Southern erosion at perihelion

The 67P nucleus has been characterized by the Rosetta mission (Glassmeier et al. 2007) and revealed to have a bi-lobed structure (Sierks et al. 2015) by OSIRIS (Keller et al. 2007) with a stable spin axis and strong seasonal characteristics. The southern hemisphere experiences a relatively short summer around perihelion in August 2015 (with equinoxes on May 2015 and March 2016), resulting in significant differences in insolation between the northern and southern hemispheres, where erosion due to sublimation of water ice is much stronger on the southern hemisphere than on the northern area (Jorda et al. 2016; Keller et al. 2017). Joint GIADA Della Corte et al. (2014) and OSIRIS observations of single dust particles and 'chunks' close to Rosetta measured the dust size distributions up to m-sizes (Fulle et al. 2016a; Ott et al. 2017). 'Chunk' is here defined as a refractories and ices aggregate of volume $>10^{-4}$ m^3, observed both in 67P and 103P comae. The OSIRIS data allowed Fulle et al. (2016a) and Ott et al. (2017) to infer the cross section of each chunk and their local space density. The chunks have a phase function similar to the nucleus one (Bertini et al. 2018), as assumed by Fulle et al. (2016a) and Ott et al. (2017), providing the chunk volume loss rate $Q_V = 8.3 \pm 2.1$ m^3 s^{-1} (namely the mass loss rate provided by Ott et al. (2017) divided by the bulk density assumed by Ott et al. (2017)) averaged from 2015 July 24 to 2015 September 15. The 1-σ error affecting Q_V, due to the chunk counts, ranges from 16 per cent (Fulle et al. 2016a) to 25 per cent (Ott et al. 2017). Q_V has been inferred from the chunk space density measured at distances <50 km from Rosetta when at terminator, by assuming a uniform dust ejection over the whole sunward solid angle (Fulle et al. 2016a; Ott et al. 2017). The chunk ejection may strongly depend on the solar phase angle, implying more anisotropic dust ejections with a peak at $\alpha < 75$ deg, which would provide $Q_V > 10$ m^3 s^{-1}. Ninety per cent of the chunks were observed when Rosetta was at phase angles $79 < \alpha < 90$ deg, the rest observed at $\alpha > 90$ deg was probably due to rocket effects pushing the chunks into the coma night side (Agarwal et al. 2016). Any significant dust ejection at $\alpha > 90$ deg has been excluded by GIADA monitoring the dust flux (Della Corte et al. 2015). As opposed to chunks, the ice mass fraction inside sub-mm dust is negligible (Gicquel et al. 2016; Fulle et al. 2018), thus its motion is not affected by rocket effects. Two chunks observed on 2015 September 28 (Ott et al. 2017) correspond to ≈0.5 per cent of the total number of measured chunks, i.e. they are not significant enough to extend the ejection time from 2015 September 15 to 28. The chunk flux is constant in the eight data sets covering 4 h on 2015 August 27 (Fulle et al. 2016a), excluding outbursts of chunks. The chunks have a radial motion with an average velocity $V_C = 1.7 \pm 0.9$ m s^{-1} (excluding the few sparse samples in Ott et al. (2017) with speed >6 m s^{-1}), thus excluding the pollution of chunks in metastable orbits (Fulle et al. 2016a). The chunk velocity was measured by means of the track length in OSIRIS images pointing in directions perpendicular to the nucleus one (Ott et al. 2017), thus ensuring a proper and precise measurement of the radial component of the chunk velocity.

When we average the volume loss rates per volume bin obtained by Fulle et al. (2016a) and Ott et al. (2017), we get that the ejected chunk volumes are ≈50 per cent in the volume bin from 10^{-3} to 10^{-2} m^3, and ≈20 per cent in the volume bins from 10^{-4} to 10^{-3} m^3, and from 0.01 to 0.1 m^3, respectively. The dust ejected in lower volume bins (<13 per cent) does not fit the definition of chunk. The strong peak of the chunk volume distribution allows us to approximate the whole chunk ejection as it all occurred in 'V_P-chunks', i.e. chunks of volume $V_P = 2.5 \times 10^{-3}$ m^3 and mass ≈1 kg if the average chunk bulk density is $\rho_C \approx \rho_N$ (the nucleus bulk density). The geometric opacity of V_P-chunks is $V_P^{2/3} \approx 0.02$ m^2 kg^{-1}, a factor 2.5 lower than assumed by Jewitt & Matthews (1999) and adopted by Schloerb et al. (2016, 2017) to convert the dust cross-section observed by MIRO Gulkis et al. (2007) at mm-wavelengths to the column density. The MIRO dust column density thus becomes 0.25 kg m^{-2} at $R = 4$ km from the centre of the nucleus of radius R_N. In a coma composed of chunks accelerating due to the drag of accelerating gas at distances $3 < R < 12$ km (Zakharov et al. 2018a), the dust column density is $Q_V \rho_C R_N^{2/3} R^{-5/3}/V_C = 0.35 \pm 0.2$ kg m^{-2}, at $R = 4$ km. This matches MIRO's measurement and predicts the column density slope of ≈− 1.7, observed by MIRO for $4 < R < 10$ km (Schloerb et al. 2016, 2017). Zakharov et al. (2018a), when taking into account both the drag by accelerating gas and the nucleus gravity, compute the lowest possible terminal chunk velocity $V_C = 2.2$ m s^{-1} for a gas loss rate of $Q_g = 10^{-4}$ kg m^{-2} s^{-1}. For $Q_g < 10^{-4}$ kg m^{-2} s^{-1}, Zakharov et al. (2018a) predict a gas density too low to lift-up the chunks.

The chunk volume ejected by 67P from 2015 July 24 to 2015 September 15 is 4.6×10^6 s × $Q_V \approx 4 \times 10^7$ m^3 and is eroded from a southern surface of ≈10 km^2 (fig. 11 right-hand in (Keller et al. 2015)), i.e. 1/5th of the total nucleus surface (Preusker et al. 2017). This means that the average erosion thickness is 4 m, much deeper than the orbital heat wave front, computed at ≈1.5 m by Capria et al. (2017). Assuming that the southern erosion occurs because of the ejection of V_P-chunks implies that the average slab thickness is of the order of $V_P^{1/3} \approx 13$ cm, which is an order of magnitude deeper than the diurnal heat wave front (Keller et al. 2015; Blum et al. 2017; Capria et al. 2017; Hu et al. 2017b). The chunk loss rate Q_V implies a total erosion in average steps of about 13 cm at the average surface loss rate of 65 m^2 s^{-1}. The largest possible water loss rate at perihelion of 3×10^3 kg s^{-1} is given by model A in fig. 5 of Keller et al. (2015). It provides a maximum water loss rate a factor 3 larger than inferred from water loss models (Hansen et al. 2016), corresponding to the water loss rate per unit area $Q_g = 3 \times 10^3$ kg s^{-1}/(10^7 m^2) ≈ 3×10^{-4} kg m^{-2} s^{-1}. The eroded southern surface is subjected to a constant insolation being in the southern polar summer (Keller et al. 2015), and results in a water loss rate of at most $65 Q_g \approx 20$ g s^{-1} from a nucleus surface of 65 m^2, i.e. a negligible mass fraction (5×10^{-6}) of the corresponding chunk loss rate. The southern erosion of 4 m corresponds to 30 chunk layers and lasts 53 d, so that one chunk layer is ejected every 1.8 d $= 1.55 \times 10^5$ s, and contains 60 chunks m^{-2}. Even adopting the available upper limit of water loss (model A in Keller et al. (2015)), during 1.8 d at most 50 kg m^{-2} of water gas sublimates without any chunk ejection, if all the chunks are ejected at once. On the other hand, if each chunk is ejected independently, one chunk is ejected from a surface of 1 m^2 every 43 min on average, during which at most 0.8 kg of water gas are ejected without any chunk ejection. Then, in a few seconds, a V_P-chunk is ejected together with <1 g of water gas. Such a difference of at least three orders of magnitude between chunk and water gas ejection rates is an evidence of how independent the ejection processes of water gas and chunks are (see Statement 2.1.1 below). At perihelion, the chunk ejection from the nucleus surface cannot be due to water gas drag, because the ice sublimation depth is much thinner than 13 cm (e.g. fig. 3 in Blum et al. (2017)). Moreover, the total outgassing from the chunk surfaces acts against its ejection. Even if the perihelion water outgassing, providing locally a negligible mass contribution, is independent of the chunk ejection, it is still coupled with the chunks being insolation-driven. Water is the densest gas, thus responsible for chunks dragging in the coma: the lifting pressure may approach 0.1 Pa (Pajola et al. 2017a), i.e. a gas drag larger than gravity up to meter-sized chunks (Harmon et al. 2004; Gundlach et al. 2015; Zakharov et al. 2018a). Any physical explanation of the fact that chunk ejection behaves independently of water ejection is beyond the aim of this paper. It follows from the observational evidence that the chunk size is >0.1 m.

These consequential lines of evidence are summarized as follows:

2.1.1 The refractory-to-ice mass ratio at 67P perihelion cannot be recovered by comparing the gas loss rate to the chunk loss rate.

2.1.2 The chunks at their ejection sample the refractory-to-ice mass ratio inside the 67P nucleus.

2.1.3 The chunks are representative of layers much deeper than the diurnal heat wave front (and deeper than samples planned to be returned by near-future cometary missions).

2.1.4 The total erosion sampled in the perihelion chunks (≈4 m) is much deeper than the orbital heat wave front.

2.1.5 The uncertainties affecting the duration and rate of the 67P chunk ejection will be hopefully reduced by models of the MIRO and VIRTIS dust data.

The chunks ejected at perihelion have a refractory-to-ice mass ratio larger than inside the nucleus, because at the time of ejection they have an upper exposed dehydrated crust, which is ejected with the chunks after being built-up by the water sublimation in 1.8 d, i.e. the average time interval between subsequent ejections of chunk layers. We compute the thickness of the dehydrated crust by means of the thermophysical model of a nucleus made up of pebbles (Blum et al. 2017), assuming a pebble size of 12 mm and providing the results listed in Table 1. The loss rate of dust of mass <0.1 kg (obtained summing the corresponding loss rates in table 8 of Fulle et al. (2016a)) and average bulk density $\rho_D =$ 785 kg m^{-3} measured by GIADA (Fulle et al. 2017) is $Q_D \approx$ 600 kg s^{-1}. Since a significant fraction of this dust is larger than 1 mm, it may contain ice (Gicquel et al. 2016; Fulle et al. 2018). During 1.8 d $=1.55 \times 10^5$ s, the dust loss rate Q_D corresponds to an average erosion of $\approx 1.55 \times 10^5$ s $\times\, Q_D/(10^7\ m^2 \rho_D) \approx 1$ cm over 10 km^2. According to the performed computations, it follows that the whole crust is eroded for the nucleus refractory-to-ice mass ratios $\delta \leq 2.5$. The water loss rate Q_g by crust dehydration is given by the crust thickness plus the average erosion in dust of mass <0.1 kg, times the unit area, times the chunk bulk density ρ_C, times the nucleus ice mass fraction divided by 1.8 d (Table 1). The nucleus ice mass fraction is $(\delta + 1)^{-1}$, where δ is the nucleus refractory-to-ice mass ratio. Since the crust thickness increases as δ increases, the numerical value of Q_g becomes independent of the refractory-to-ice mass ratio (inside the nucleus and the chunks) and it is a factor of 30 lower than predicted by model A in Keller et al. (2015), and a factor of 7 lower than predicted by model C in Keller et al. (2015). The Q_g values provided by Keller et al. (2015) require that a minor fraction of the nucleus surface is active. On the other hand, the Q_g value provided by Table 1 is consistent with a crust dehydration of the whole sunlit nucleus surface. The nucleus refractory-to-ice mass ratios δ are converted to the chunk ones $\Delta = \delta/(1 - \chi)$, where χ is the crust volume fraction in the ejected slab computed by the pebble thermophysical model. The values of Δ are close to δ for $\delta < 5$, while become a factor of two larger for $\delta > 20$. Table 1 allows us to convert the refractory-to-ice mass ratio inferred for the chunks to that inside the 67P nucleus: $\Delta \geq 4.3$ implies inner nucleus values $\delta \geq 4$. Changes of such a conversion due to a relatively thicker crust (with respect to the chunk size) of the chunks populating the volume bin from 10^{-4} to 10^{-3} m^3 are balanced by a relatively thinner crust for the similar volume percentage of 20 per cent of the chunks in the volume bin from 0.01 to 0.1 m^3. The contribution of supervolatiles, lacking at chunk depths, lowers by 20 per cent the nucleus refractory-to-ice mass ratios, and is taken into account in Sections 2.6 and 5.

An alternative scenario is that the chunks are ejected as dehydrated sheets of area, e.g. >1 m^2 each and thickness <2 mm, and then reshaped into chunks by the gas drag in the coma (Blum et al. 2017). Differential gas pressure would probably break up these thin sheets. This scenario is inconsistent with the possible presence of distributed water sources and the observed water sublimation from dust deposits (see the next subsection), and will be not further considered.

2.2 Dust fallout

Smooth plains observed mainly in the northern 67P hemisphere of the nucleus are evidence of dust fallout (Thomas et al. 2015), explained as a dominant mass transfer from south to north occurring mainly around perihelion (Mottola et al. 2015; Keller et al. 2017; Pajola et al. 2017a). The cross-section distribution of pebbles in Sais region, with a strong peak at ≈25 cm (Pajola et al. 2017a), shows that these deposits were built-up by chunks of at least similar size (see the discussion in Section 2.1), and thus confirms the chunk mass distribution observed in the 67P coma (Fulle et al. 2016a; Ott et al. 2017).

The deposits of pebbles in Hapi, Sais, and Agilkia regions have been best explained in terms of 'self-cleaning' (Pajola et al. 2017a), and summarized here. The chunks ejected near perihelion fall back over the whole nucleus surface. The fallout is generally uniform, and the nucleus outgassing (even on the southern surface not ejecting the chunks) is too low to prevent the fallout. Break-up of the chunks at the surface impact is inconsistent with the size distributions observed in the deposits, with a dominant cross-section larger than that observed in the coma. As the outbound equinox approaches, seasonal changes decrease the outgassing from where chunks were ejected around perihelion, and increase the outgassing where fallout occurred around perihelion. This outgassing (or rolling down the cliffs) self-cleans the fallout, nearly completely where dust deposits are not observed, and partially where dust deposits are observed. Outbound, the self-cleaning in the Hapi region is negligible, thus preserving the chunks intact up the the next inbound orbit.

Table 1. Increase of the refractory-to-ice mass ratio from the nucleus to the chunks due to the crust dehydration after 1.8 d of perihelion insolation with the average erosion of 1 cm.

Refractory-to-ice mass ratio in the nucleus, δ	Crust thickness cm	Volume fraction of crust, χ	Refractory-to-ice mass ratio in the chunks, Δ	Water loss rate Q_g kg m^{-2} s^{-1}
2.5	0	0/13 = 0.0%	2.5/1. = 2.5	10^{-5}
5.0	1	1/13 = 7.7%	5./0.923 = 5.4	10^{-5}
10.	3	3/13 = 23.%	10./0.77 = 13.	10^{-5}
20.	5	5/13 = 38.%	20./0.62 = 32.	10^{-5}

Hapi's outgassing is significant only from 2.5 to 4 au outbound (corresponding to 6 months $=1.6 \times 10^7$ s), when the outgassing is <0.1 per cent of the water loss rate observed in Bes or Wosret regions during perihelion (Keller et al. 2017; Pajola et al. 2017a), where the largest possible water loss is provided by model A in Keller et al. (2015). Outbound, Hapi's pure ice chunks of 1 kg and cross-section $\sigma_C \approx V_P^{2/3} \approx 0.02$ m^2 would eject a water mass of $<1.6 \times 10^7$ s $\times$ 10^{-3} $\times$ $(\sigma_C Q_g) \approx 0.1$ kg, in case of model A in Keller et al. (2015). It follows that outbound each chunk in Hapi ejects <10 per cent of its ice mass.

At perihelion in Bes, fresh ice is exposed to sunlight by the chunk ejection every 1.8 d on average, so that the outgassing is coming from the dehydration of the crust and, according to the adopted dehydration model, is independent of the ice mass fraction in the nucleus (Section 2.1 and Table 1). On the opposite, Hapi does not eject chunks, it ejects sub-cm dust only (Rotundi et al. 2015). Hapi acts as a chunk deposit with a thickness of meters, as exemplified by the dune-like forms in this region (El-Maarry et al. 2015). In Hapi, fresh ice is exposed to sunlight by water ice migration to the surface (De Sanctis et al. 2015) and by the continuous removal of the dehydrated crust, so that the outgassing is coming from the interior of the chunks deposited on Hapi's surface and is given by the ice mass fraction in the chunks.

Here is a summary of the described processes:

2.2.1 During the 67P outbound orbit, chunks deposited in Hapi region retain >90 per cent of the water ice they contain at their landing.

2.2.2 Layers made of deposited chunks prevent any outgassing from below: outgassing from deposits is due to water vapour diffusing inside each chunk.

2.2.3 Hapi is a dust deposit, nevertheless inbound outgases a water mass similar to the average northern surface (Zakharov et al. 2018b).

2.2.4 Since deposits cover ≈27 per cent of the nucleus surface (Thomas et al. 2018), the total fallout must be much larger than observed in the deposits.

2.2.5 Following 2.2.1, the ice mass fraction of Hapi's chunks is here approximated to be that at chunk landing, which outbound stops the chunk sublimation.

The ice mass fraction Z_C on the northern nucleus hemisphere has been estimated by the pebble thermophysical model (Blum et al. 2017) assuming a dehydrated crust of 1 cm, taking into account the inward radiative transfer and fitting the increasing water loss rate and nucleus surface temperature measured by MIRO. A crust of 1 cm is consistent with the observed ejection of at most cm-sized dry dust (Rotundi et al. 2015). Hapi's chunk crusts significantly thicker than 1 cm would imply a refractory-to-ice mass ratio inside the nucleus >6 (Table 1). The ice mass fraction results $0.025 < Z_C < 0.05$, is constant inbound at heliocentric distances from 3.6 to 3.0 au below the dehydrated crust, and is consistent with the water-ice mass fraction in the frost at Hapi's sunrise measured by VIRTIS (Coradini et al. 2007). Hapi's frost (disappearing just after sunrise) is due to the night accumulation of ice (sublimating from Hapi's warm interior) on Hapi's cold surface (De Sanctis et al. 2015). Other thermophysical models, independent of the nucleus pebble structure, have found similarly low Z_C values (Hu et al. 2017a,b). Fluid-dynamical codes of 67P gas coma, observed inbound at heliocentric distances >3 au, have provided the Hapi's active area fraction ranging from 1.2 per cent (homogeneous model) to 7.5 per cent (Hapi's-dominated inhomogeneous model) (Marschall et al. 2017). Other more general time-dependent fluid-dynamical coma models provide the best fit of the same data assuming inhomogeneous solutions with Hapi being a minor water contributor (Zakharov et al. 2018b). All these 3D coma models take into account the local insolation, the radiation reflection from facing surfaces, and gas outflow focussing due to the nucleus shape, and show that any adopted inhomogeneous active area fraction over the nucleus surface is still arbitrary. Tests performed by thermophysical models of homogeneous nuclei show that the dumping of the active area fraction due to the dehydrated crust (up to a factor 5 between models A and C in Keller et al. 2015) is balanced by the temperature increase in case of low ice mass fractions below the dehydrated crust (active area fractions increased up to a factor 3 (Hu et al. 2017b)). This result can be applied to Hapi's deposits, because perihelion fallouts are generally homogeneous, thus explaining the similar ranges of Z_C and of the active area fractions discussed above. In non-homogeneous surfaces, e.g. wind tails due to the aeolian erosion of former deposits (Mottola et al. 2015), the local ice mass fraction may not be linked to the active area fraction. The inconsistent results affecting the active area fractions provided by 3D coma models will be hopefully reduced by fitting not only the local coma water density, but also the water coma column density and temperature provided by MIRO and VIRTIS. Following the discussion above, in the next subsections, we will consider equally probable all values $0.012 \leq Z_C \leq 0.075$.

2.3 Water loss rate

Rosetta has not yet determined an agreed value of the 67P water loss rate at perihelion. According to ROSINA Balsiger et al. (2007) data, the total water mass ejected from August 2014 to September 2016 is $(6.4 \pm 0.9) \times 10^9$ kg (Hansen et al. 2016), a mass about three times larger than measured by MIRO (Marshall et al. 2017). Such a difference is $>3\sigma$ and is mostly observed during two months around perihelion. Observations of the Lyman-α coma, performed from 2015 September 7 to 13 at a distance of 1.8 au from 67P, provide water loss rates of 450 ± 150 kg s^{-1} (Shinnaka et al. 2017), i.e. between ≈150 kg s^{-1} provided by MIRO (Marshall et al. 2017) and ≈900 kg s^{-1} provided by ROSINA (Hansen et al. 2016), when Rosetta was at $R \approx 350$ km from the nucleus. This implies the chunk average flight time $\tau = R/V_C \approx 2 \times 10^5$ s, close to the dehydration time in Table 1. Ice in chunks cannot sublimate completely, unless their ice mass fraction Z_C is very low. In fact, since $Q_V/V_P \approx 3500$ chunks of about 1-kg mass each are ejected every second, a complete ice sublimation from all chunks is consistent with Lyman-α data only if $Z_C < 13$ per cent, or even much lower if most coma water comes from the nucleus surface. However, a perfectly dry fallout is inconsistent with the observation of the diurnal cycle of ice in Hapi (De Sanctis et al. 2015), which is a dust deposit. In the following paragraphs, we explain this fact by a dehydrated crust quenching the chunk outgassing during their flight, thus preserving some ice in the chunk interior. This explanation is not unique: the actual constraint is that Hapi's chunks must maintain the ice mass fraction Z_C discussed in the previous subsection. Whatever the chunk outgassing is, it will be taken into account by the water loss rate Q_{WC} from all flying chunks, which will be assumed to cover all the possible ranges, from few to many distributed water sources.

During its flight, each chunk, probably rotating, dehydrates its surface of $5 \times \sigma_C \approx 0.1$ m^2 not yet covered by the crust. Observations of rotating particles have provided the most probable rotating frequency <0.5 Hz (Fulle et al. 2015). Models of spheroidal dust particles forced to rotate by the gas drag provide even lower frequencies (≈0.01 Hz (Fulle et al. 2015; Ivanovski et al. 2017a,b)). Computations performed assuming fast rotating chunks provide Q_g values lowered by a factor of 2/3 with respect to those listed in Table 1. Each chunk releases at least $\frac{10}{3}\sigma_C Q_g \tau \approx 0.13$ kg of water (according to the Q_g values in Table 1), i.e. 13 per cent of the chunk mass, implying a distributed water source $Q_{WC} \approx 0.13\rho_C Q_V \approx 500$ kg s^{-1}, i.e. the total water production rate observed by Lyman-α observations (Shinnaka et al. 2017). Other available 67P thermophysical models (Keller et al. 2015) compute a water loss rate lower than in Table 1 only if the chunk refractory-to-ice mass ratio ranges from >6 (model C) to >30 (models A and B; we assume homogeneous chunks, so that their active area fraction provides an upper limit of their ice mass fraction (Hu et al. 2017b)). During the chunk flight, its erosion is negligible: the total dust loss of mass <0.1 kg from chunks is <15 per cent of their mass (subsection 2.1), corresponding to a crust average thickness of <0.15 kg $/(5\sigma_C\rho_C)$ ≈ 3 mm. Therefore, the ice mass enclosed in the crust would be 0.19 kg per chunk in case of a refractory-to-ice mass ratio of 2.5 (crust of 1 cm, Table 1), whereas the ice mass enclosed in the crust would be 6 g only in case of a refractory-to-ice mass ratio of 10 (crust of 4 cm, Table 1), much more consistent with mostly inactive chunks at $R > 350$ km than a chunk crust of 1 cm. All thermophysical models predict a water loss rate from the chunks consistent with Lyman-α observations only if the chunk refractory-to-ice mass ratio is >6. However, models A, B, and C in Keller et al. (2015) predict continuing chunk erosion and outgassing if the chunk flight lasts more than the average travel time τ, implying a water loss rate from flying chunks inconsistent with Lyman-α observations (unless most chunks fall back after a flight lasting $<\tau$, subsections 2.4 and 2.5). Only a dehydrated crust thick at least 2 cm seems to significantly quench the outgassing after the crust dehydration, lasting $<\tau$. It follows that the chunks observed close to Rosetta (Fulle et al. 2016a; Ott et al. 2017) have almost completed their outgassing, maintaining the ice mass fraction Z_C inside, to be consistent with Hapi's ice (De Sanctis et al. 2015). Chunk outgassing implies that at perihelion VIRTIS and OSIRIS observe a dust column density shallower than MIRO, due to distributed dust sources, coming from the chunk erosion in 67P coma, similar to that affecting the nucleus surface (Subsec 2.1), but negligibly affecting the chunk mass, as computed above.

Some chunks fall back in Hapi, which is in polar night up to 2 au outbound (Pajola et al. 2017a), so that the chunk surface becomes suddenly much colder than its interior, forcing all the water vapour still sublimating from the chunk interior to condense close to its crust surface (De Sanctis et al. 2015). This process, equivalent to ice diffusion, transfers some ice in the crust, making the chunks in the deposits ready to outgas during the next inbound orbit. Inbound, from 2014 August to 2015 February (i.e. 1.6×10^7 s), the average dust loss rate is $Q_D \approx 30$ kg s^{-1} (Fulle et al. 2016a), corresponding to the average erosion of $1.6Q_D/\rho_C \approx 0.1$ m over 10 km^2 (0.5 m if all the dust is lost from Hapi only), i.e. at least one chunk. It is sufficient that part of the ice mass fraction Z_C is transferred into the chunk crust by ice diffusion, to trigger the ice sublimation in the chunk on the nucleus surface, then its surface erosion by dust ejection, the exposition of further inner ice, with the erosion of the following dust layer, up to the complete dissipation of the surface chunk. During the outgassing from Hapi, the ejected sub-cm dust particles are completely dry, because they are fragments of the chunk dehydrated crust (Rotundi et al. 2015; Fulle et al. 2018). This is confirmed by the agreement between the MIRO and ROSINA water loss rates during the inbound outgassing (Hansen et al. 2016; Marshall et al. 2017), which implies negligible distributed water sources from dust.

The described frame is summarized here:

2.3.1 Distributed water sources outside the Rosetta orbit are much less than inside (Lyman-α water loss rate is less than ROSINA one).

2.3.2 Hapi's outgassing ejects sub-cm perfectly dry dust particles (Rotundi et al. 2015; Fulle et al. 2018): they are fragments (pebbles) of the chunk dehydrated crust.

2.3.3 At perihelion, the chunk outgassing vanishes at Rosetta distances, after having lowered the chunk ice mass fraction to Z_C.

In order to compute a first estimate of the 67P dust-to-gas ratio around perihelion, we consider the water loss rate averaged from 2015 July 24 to 2015 September 15 (Ott et al. 2017). During this period, ROSINA data provide an average water loss rate of 660 ± 200 kg s^{-1}, with a dust-to-gas mass ratio of $Q_V\rho_C/(660 \pm 200) = 6 \pm 2$. MIRO data provide an average water loss rate of 220 ± 80 kg s^{-1}, with a dust-to-gas mass ratio of $Q_V\rho_C/(220 \pm 80) = 18 \pm 5$. These two inconsistent results can be solved by two alternative end-case scenarios, i.e. many and few distributed water sources:

2.3.4 The difference is explained in terms of distributed water sources. MIRO, a remote sensing instrument, observes the water coma (in optically thin IR-lines) close to the nucleus surface, measuring the water loss mostly from the nucleus surface. ROSINA, an in-situ instrument, observes at Rosetta location, i.e. at hundreds km from the nucleus around perihelion, measuring the water loss from the nucleus but also from the chunks. This scenario suggests that the average perihelion water loss rate from the chunks is $Q_{WC} = 550$ kg s^{-1}, consistent with the Q_{WC} prediction above. The average perihelion water loss rate from the nucleus surface becomes 110 kg s^{-1} (still marginally consistent with MIRO's value Marshall et al. (2017)), consistent with the water loss rate computed in Table 1 over the southern nucleus surface of ≈10 km^2 (Keller et al. 2015), with a dust-to-gas ratio of 36 ± 15. However, since $Q_g \ll 10^{-4}$ kg m^{-2} s^{-1}, this Scenario seems inconsistent with the chunk drag by gas (Section 2.1), so that it is less probable than the following one.

2.3.5 The difference is due to uncertainties in the models deriving the water loss rate by the three quoted techniques (Lyman-α, ROSINA and MIRO). In this case, the average perihelion 67P water loss rate is the average of the three values, i.e. 500 ± 300 kg s^{-1}, and the dust-to-gas mass ratio in the southern eroded surface is 8 ± 4. Opposite to Scenario 2.3.4, this scenario (i) considers the case of negligible distributed water sources from the chunks since their ejection from the nucleus surface, (ii) is consistent with dominant Hapi's outgassing during the inbound orbit, as discussed in the next subsections, (iii) is coherent with models of the distributed halide sources (De Keyser et al. 2017). This scenario requires a water loss rate Q_g larger than the value in Table 1, i.e. either a dehydrated crust surface $>\sigma_C$ per chunk before the ejection, or pebbles of diameter >12 mm providing a thicker dehydrated crust.

2.4 Nucleus lost mass

Rosetta orbits analysis has constrained the total mass lost by the 67P nucleus to $(9 \pm 6) \times 10^9$ kg (Godard et al. 2017). When compared to the total water losses discussed in the previous subsection, we get a total dust mass loss of $(9 \pm 6 - 2.2) \times 10^9 = (6.8 \pm 6) \times 10^9$ kg according to MIRO data, and of $(9 \pm 6 - 6.4) \times 10^9 = (2.6 \pm 6) \times 10^9$ kg according to ROSINA data. Since negative lost masses have no physical meaning, we correct the total dust loss into $(4.3 \pm 4.3) \times 10^9$ kg according to ROSINA data. These dust masses provide the average dust-to-gas mass ratios in the lost material of 0.7 ± 0.7 and 3.1 ± 2.7, respectively. The large difference with the values found in the Scenarios 2.3.4 and 2.3.5 has been already explained in terms of dust fallout (Fulle et al. 2017), and allows us to discuss how the refractory-to-ice mass ratio inside a cometary nucleus is linked to the dust-to-gas mass ratio in the lost material.

The chunks ejected at perihelion are a mixture of refractory material and water ice. Since the dust erosion per chunk is <3 mm (subsections 2.1 and 2.3), the chunks maintain their volume and refractory mass while sublimating their ices during their flight in the 67P coma. At the nucleus, the chunk mass ejection rate is $Q_{RC} + Q_{IC}$, where Q_{RC} is the pure refractory mass ejection rate and Q_{IC} is the pure ice mass ejection rate. The chunk volume ejection rate is $Q_V = Q_0/\rho_0$, where $Q_0 = 8300 \pm 2100$ kg s^{-1}, assuming a chunk bulk density of $\rho_0 = 10^3$ kg m^{-3} (Fulle et al. 2016a; Ott et al. 2017). Since the chunks are ejected as pieces of the nucleus, their ejection rate is $Q_{RC} + Q_{IC} = \rho_N Q_V$, where $\rho_N = 538$ kg m^{-3} is the average nucleus bulk density (Preusker et al. 2017). If the nucleus macroporosity had a scale larger than the chunk size, then the chunk bulk density would be $\rho_N \leq \rho_C \leq \rho_D$, and this would increase the chunk mass ejection rate (ρ_D is the average dust bulk density measured by GIADA (Fulle et al. 2017)). Chunks at Rosetta distances maintain the ice mass fraction Z_C (Statement 2.3.3 and related discussion), and their mass loss rate becomes $Q_C = Q_{RC} + Q_{IC} - Q_{WC}$. The chunk bulk density decreases from ρ_N, at ejection, to $\rho_C = Q_C/Q_V$ at Rosetta.

During the chunk flight in the 67P coma, distributed water sources are measured by the water mass loss rate Q_{WC} from the chunks. Here we consider two alternative end-cases, with the real unknown value of Q_{WC} somewhere in between:

2.4.1 In the case of many distributed water sources (Scenario 2.3.4), $Q_{WC} = 550$ kg s^{-1}, i.e. 5/6 of the 67P water loss rate.

2.4.2 In the case of few distributed water sources (Scenario 2.3.5), $Q_{WC} = 25$ kg s^{-1}, i.e. 1/20 of the 67P water loss rate (Fulle et al. 2016b).

The pure ice fallout mass rate is (Statement 2.3.3) $Q_{IC} - Q_{WC} - Z_C Q_L$, and the pure refractory fallout mass rate is $Q_{RC} - (1 - Z_C)Q_L$, where Q_L is the 67P chunk mass loss rate taking into account the chunk fallout not directly observable by Rosetta, so that $Q_L < Q_C$. Here, we neglect the mass fraction of chunks injected into orbits bound around the nucleus up to the following aphelion, which is <0.1 per cent of the total ejected mass for a nucleus of 67P's mass (Fulle 1997; Rotundi et al. 2015). Since Q_L is lost, it can be computed by the average perihelion water loss rate times the dust-to-gas mass ratios observed in the lost material, i.e. 0.7 in Scenario 2.3.4, and 2 in Scenario 2.3.5 (2 is the average of the values provided by the ROSINA and MIRO data). It follows that $Q_L = 460$ kg s^{-1} in Scenario 2.3.4, and $Q_L = 1000$ kg s^{-1} in Scenario 2.3.5. In Scenario 2.3.4, $Q_L < Q_D$ (Section 2.1), suggesting that also the dust masses in the range between 10 and 100 g should be classified as chunks. Since the loss rate in dust of mass <10 g is $Q_D \approx 260$ kg s^{-1} (Fulle et al. 2016a), the chunk loss rates are actually reduced to $Q_L = 200$ kg s^{-1} in Scenario 2.3.4, and to $Q_L = 740$ kg s^{-1} in Scenario 2.3.5. The average dust loss rate from 2015 July 24 to 2015 September 15, observed in the 67P dust tail and trail, is $Q_D \approx 2 \times 10^3$ kg s^{-1}, but that is strongly dependent on the assumed extrapolation of the dust size distribution from 0.1 to 0.8 m (Moreno et al. 2017): these chunks are too big to be actually observed in tails and trails. Moreover, the power index of the chunk differential size distribution from 1 to 10 cm is -2 (Fulle et al. 2016a; Ott et al. 2017) rather than -3.6 (Moreno et al. 2017), because trails are depleted of the falling back chunks, so that 67P tail and trail data are consistent with $Q_0 = 8300 \pm 2100$ kg s^{-1}, and with the Scenarios 2.3.4 and 2.3.5 if most of the chunks fall back on the nucleus.

Following Statements 2.2.1, 2.2.2, 2.2.5, 2.3.2, and 2.3.3, the ice mass fraction in dust deposits is given by the pure ice fallout rate divided by the total fallout rate, namely

$$Z_C = \frac{Q_{IC} - Q_{WC} - Z_C Q_L}{[Q_{RC} - (1 - Z_C)Q_L] + [Q_{IC} - Q_{WC} - Z_C Q_L]} \tag{1}$$

which uniquely constrains the pure ice and pure refractory mass ejection rates ejected in the chunks

$$Q_{IC} = (1 - Z_C)Q_{WC} + Z_C Q_V \rho_N \tag{2}$$

$$Q_{RC} = (1 - Z_C)(Q_V \rho_N - Q_{WC}) \tag{3}$$

The results are reported in Tables 2–5 for the four combinations of Scenarios 2.3.4, 2.3.5, $Z_C = 7.5$ per cent and $Z_C = 1.2$ per cent (Section 2.2), respectively. Let's consider Table 2. Equations (2) and (3) provide $Q_{IC} = 840$ kg s^{-1} and $Q_{RC} = 3610$ kg s^{-1}, i.e. a chunk ice mass fraction of 19 per cent; $Q_{WC} = 550$ kg s^{-1}, water lost by sublimation into distributed sources; $Q_{IC} - Q_{WC} - Z_C Q_L = 275$ kg s^{-1}, ice falling back over the whole nucleus surface; $Q_{RC} - (1 - Z_C)Q_L = 3425$ kg s^{-1}, refractory material falling back over the whole nucleus surface. Thus Hapi's deposits contain the ice mass fraction $Z_C = 7.5$ per cent (Subsec. 2.2), which is the ice mass fraction inside a 0.37 kg chunk with a refractory-to-ice mass ratio of 4 (Table 1), enclosed by a 0.63 kg dehydrated crust with a thickness of 2 cm, fitting that in Table 1 assuming an erosion of 1 cm. Tables 3–5 can be also read in the same way but with different values of parameters Q_L, Q_{WC} and Z_C. In case of few distributed water sources, $Q_{WC} = 25$ kg s^{-1} implies that only 5 per cent of the chunk surface outgasses during its flight in the 67P coma (see the discussion in Section 2.3), so that 95 per cent of the chunk surface dehydrates before its ejection (discussion in the Scenario 2.3.5). This is consistent with the gas loss rate from the nucleus surface listed in Tables 2 and 5. The ice mass fraction of 7.5 per cent corresponds to the nucleus Refractory-to-Ice mass ratio of 4 reported above. An ice mass fraction of 1.2 per cent (Table 5) is inside a 0.11 kg chunk, with a refractory-to-ice mass ratio of 9, enclosed by 0.89 kg of dehydrated

Table 2. Refractory-to-ice ratio vs. dust-to-gas ratio in 67P: Hapi's active area fraction = 7.5%, many distributed water sources, $\rho_C = 470$ kg m^{-3}. In the last column, the loss rate of 260 kg s^{-1} of dust of mass <10 g is taken into account.

Physicalp process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Gas rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Southern Erosion	3610	840	110		43. = (4450 + 260) / 110
Into chunks at ejection	3610	840		4.3 (19.%)	
Into gas from chunks			550		
Into fallout	3425	275		12. (7.5%)	
Into lost material	185	15	660	12. (7.5%)	0.7 = (200 + 260) / 660

crust with a thickness of 3.5 cm (Table 1). It follows that a chunk refractory-to-ice mass ratio of 11 or 55, at the ejection, corresponds to a nucleus Refractory-to-Ice mass ratios of 4 or 9, respectively. Alternatively, if the upper chunk crust is a factor of 2 larger than in Table 1 (Scenario 2.3.5), a chunk refractory-to-ice mass ratio of 11 or 55 corresponds to a nucleus refractory-to-ice mass ratio of 7.5 or 15, respectively (Table 1). If the crusts computed above are sufficiently thick to quench the chunk outgassing, then the chunk flights may last weeks, otherwise most of the chunks fall back after a flight of less than 2 d (Section 2.3).

In all possible cases sampled by Tables 2–5, the low dust-to-gas mass ratios in the lost material correspond to much larger dust-to-gas mass ratios at the ejection: 0.7 corresponds to 43 (close to the value of 36 estimated in the Scenario 2.3.4), whereas 2 corresponds to 10 (close to the value of 8 estimated in the Scenario 2.3.5). However, since the chunk ejection is independent of the nucleus water outgassing (Section 2.1), the dust-to-gas ratio at the surface has little physical meaning. The low dust-to-gas mass ratio in the lost material corresponds also to a much larger refractory-to-ice mass ratio in the chunks, which, according to Statements 2.1.2, 2.1.3, 2.1.4 and Table 1, samples the pristine refractory-to-ice mass ratio of a comet. For many distributed water sources (5/6 of the ROSINA water loss rate, Scenario 2.3.4), a dust-to-gas mass ratio of 0.7 in the lost mass corresponds to a range for the Refractory-to-Ice mass ratio inside the chunks at ejection from 4.3 to 6.4, corresponding to a refractory-to-ice mass ratio inside the nucleus ranging from 4 to 6 (Table 1). For few distributed water sources (1/20 of the 67P water loss rate, Scenario 2.3.5), the dust-to-gas mass ratio of 2 in the lost material corresponds to a range for the refractory-to-ice mass ratio inside the chunks at ejection from 11 to 55, corresponding to the refractory-to-ice mass ratio inside 67P ranging from 4 to 15, either assuming a crust dehydration over 95 per cent of the chunk surface before ejection, or a nucleus crust a factor of 2 thicker than in Table 1. The uncertainty of 25 per cent affecting Q_0 implies a similar uncertainty in the dust-to-gas and refractory-to-ice mass ratios reported in Tables 2–5. Since the diurnal dust fallout occurs in all comets, we conclude that the dust-to-gas mass ratio observed in the lost material (e.g. by fitting the spacecraft motion or trail IR observations) underestimates by a factor 6 ± 3 the nuclei refractory-to-Ice mass ratio.

2.5 Chunk fallout mass and rate

The fraction of fallout mass is

$$f = \frac{(Q_{RC} - (1 - Z_C)Q_L) + (Q_{IC} - Q_{WC} - Z_C Q_L)}{Q_{RC} + Q_{IC}} \quad (4)$$

which becomes

$$f = 1 - \frac{Q_{WC} + Q_L}{Q_{RC} + Q_{IC}} \quad (5)$$

Equation (5) provides $f = 83.2$ per cent for the Scenario 2.3.4 and $f = 80.6$ per cent for the Scenario 2.3.5, consistent with Statement 2.2.4. equation (5) depends on Q_L, whereas equations (2) and (3) do not. Since in equations (1) to (5), only the quantity Q_L depends on the dust-to-gas ratio in the lost material, then the fallout mass depends on this ratio, whereas the Refractory-to-Ice mass ratio inside the nucleus does not.

Assuming a uniform chunk ejection over the sunward solid angle (Section 2.1), we link $f = (81.9 \pm 1.3)$ per cent to $\alpha_f = 79.5 \pm 0.8$ deg provided by $\cos \alpha_f = 1 - f$. A chunk ejection with a strong peak at low solar zenithal angles implies $\alpha_f \ll 80$ deg. Most chunks ejected at an angle $\alpha < \alpha_f$ with respect to the solar direction fall back on the nucleus, whereas most of those ejected at $\alpha > \alpha_f$ are lost in space. This is consistent with: (i) chunk ejection and fallout on January 2016 (Agarwal et al. 2016), showing that the outgassing from the chunks pushes them back towards the nucleus at small α values and far from it at large α values; (ii) chunk injection into bound orbits, occurring at well defined α values: close to these α values, chunks can fall back on the nucleus, whereas at larger α values, chunks are lost in space (Fulle 1997). This explains why $Q_L \ll Q_C$, i.e. why OSIRIS could detect so many chunks escaping the nucleus gravity field (Ott et al. 2017): they were always observed when Rosetta was close to the terminator (Fulle et al. 2016a; Ott et al. 2017). Since Rosetta safety policy prevented perihelion orbits at low phase angles, we have no data to check if the observed chunk space density around Rosetta would have been much lower in subsolar Rosetta orbit (at nucleus distances of hundreds of km) than in the performed terminator orbits.

Up to now, equation (5) provides the only possible estimate of the falling back mass. From 2015 July 24 to September 15, 67P tail and trail data constrain the average dust loss rate to $\approx 2 \times 10^3$ kg s^{-1} (Moreno et al. 2017), mostly depending on chunks remaining too close to the comet nucleus to be observed in tails and trails. Therefore, $f = 90$ per cent and $f = 63$ per cent make this loss rate consistent with the measured nucleus lost mass in case of many ($Q_L = 200$ kg s^{-1}) or few ($Q_L = 740$ kg s^{-1}) distributed water sources, respectively. A fraction $f < 20$ per cent has been estimated by modelling the fallout of the chunks showing a sunward outgassing on 2016 January 6, assuming a fallout occurring within a few nucleus rotations (Keller et al. 2017). Another fallout model neglecting the dust outgassing provides $f \approx 20$ per cent at perihelion (Lai et al. 2016), considering however dust always much smaller than the chunks actually observed in the deposits (Pajola et al. 2017a). After perihelion, the dust phase function shows a systematic dependence on the nucleus distance, being close to the nucleus phase function at distances <100 km (Bertini et al. 2018). This evidences that after perihelion the nucleus is surrounded by a cloud of chunks orbiting the nucleus and slowly collapsing on it (Bertini et al. 2018). Inside a distance of 100 km, the light scattering is dominated by these

Table 3. Refractory-to-Ice ratio vs. dust-to-gas ratio in 67P: Hapi's active area fraction $= 7.5\%$, few distributed water sources, $\rho_C = 530$ kg m^{-3}. In the last column, the loss rate of 260 kg s^{-1} of dust of mass <10 g is taken into account.

Physical process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Gas rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Southern Erosion	4095	355	475		10. = (4450 + 260) / 475
Into chunks at ejection	4095	355		11.5 (8.%)	
Into gas from chunks			25		
Into fallout	3410	275		12. (7.5%)	
Into lost material	685	55	500	12. (7.5%)	2. = (740 + 260) / 500

Table 4. Refractory-to-ice ratio vs. dust-to-gas ratio in 67P: Hapi's active area fraction $= 1.2\%$, many distributed water sources, $\rho_C = 470$ kg m^{-3}. In the last column, the loss rate of 260 kg s^{-1} of dust of mass <10 g is taken into account.

Physical Process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Gas rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Southern Erosion	3850	600	110		43. = (4450 + 260) / 110
Into chunks at ejection	3850	600		6.4 (13.%)	
Into gas from chunks			550		
Into fallout	3652	48		80. (1.2%)	
Into lost material	198	2	660	80. (1.2%)	0.7 = (200 + 260) / 660

Table 5. Refractory-to-ice ratio vs. dust-to-gas ratio in 67P: Hapi's active area fraction $= 1.2\%$, few distributed water sources, $\rho_C = 530$ kg m^{-3}. In the last column, the loss rate of 260 kg s^{-1} of dust of mass <10 g is taken into account.

Physical process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Gas rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Southern Erosion	4370	80	475		10. = (4450 + 260) / 475
Into chunks at ejection	4370	80		55. (1.8%)	
Into gas from chunks			25		
Into fallout	3640	45		80. (1.2%)	
Into lost material	730	10	500	80. (1.2%)	2. = (740 + 260) / 500

chunks, suggesting that their mass fraction is much larger than the 20 per cent estimated by Keller et al. (2017). Probably, ≈20 per cent of the ejected chunks fall back on the nucleus within a few nucleus rotations (Keller et al. 2017), and >60 per cent fall back during many months, even after the post-perihelion equinox (Bertini et al. 2018). Values of V_C larger than the escape speed imply escaping chunks. Therefore, the chunk sunward outgassing is actually driving the fallout (Agarwal et al. 2016) more efficiently for sunward chunk velocity (thus ineffective at terminator). It follows that Ott et al. (2017) measured the average chunk ejection speed, not the tail of the chunk velocity distribution. This would make inconsistent the MIRO dust column density with the OSIRIS one (Section 2.1), due to both larger chunk loss rates and to chunk average speeds lower than the values reported in Section 2.1. Models of accelerating chunks, taking into account both the nucleus gravity and the drag by accelerating gas (Zakharov et al. 2018a), predict that the chunk velocity distribution has a peak at $V_C > 2.2$ m s^{-1} at terminator, where the chunk outgassing does not decelerate the chunk. For chunks ejected sunward, the same models predict that the sublimation of 10 g of water lasting 2×10^5 s and starting at 0.1 km from the nucleus surface produces a rocket effect stopping a chunk of 1 kg mass at a nucleus distance of less than 200 km, with $Q_{WC} \approx 40$ kg s^{-1}, consistent with Tables 2–5.

In summary, the chunk leaves the inner coma (defined as about six nucleus radii (Zakharov et al. 2018a; Gerig et al. 2018)) with an average velocity $V_C = 1.7 \pm 0.9$ m s^{-1} larger than the escape speed. Outgassing decelerates chunks ejected at low phase angles (i.e. $\alpha < \alpha_f$) to a radial speed below the escape velocity (Agarwal et al. 2016) leading the chunk entering a very eccentric bound orbit (Fulle 1997) with e.g. an orbital period of about one month and a semimajor axis $a = 50$ km. The chunk ougassing vanishes just after two d to be consistent with Lyman-α data (Section 2.3), probably due to a fast crust dehydration (Section 2.1 and Table 1). The chunk orbit is perturbed by the nucleus gas drag never taken into account by fallout models (Thomas et al. 2015; Lai et al. 2016; Keller et al. 2017), implying an a and e decrease per orbit (Bertini et al. 2018)

$$\Delta a = -\frac{4\pi\sigma_C Q_g R_N^2}{M_C}\sqrt{\frac{(\gamma+1)(1+e^2/2)^2 a}{(\gamma-1)(1-e^2)^3 G M_N}} \tag{6}$$

$$\Delta e = -\frac{3\pi e\sigma_C Q_g R_N^2}{M_C}\sqrt{\frac{\gamma+1}{(\gamma-1)(1-e^2) a G M_N}}, \tag{7}$$

where e is the chunk orbital eccentricity, $R_N \approx 2$ km and M_N are the nucleus radius and mass ($GM_N = 667$ m^3 s^{-2}), σ_C and M_C are the chunk cross section and mass, γ is the specific heat ratio of the coma gas, and Q_g is the water loss rate per unit area reported in Table 1 (Zakharov et al. 2018a). Equation (6) provides $\Delta a = -0.7$ km per orbit if $e = 0.7$ (pericentre of 15 km), $\Delta a = -1.2$ km per orbit if $e = 0.8$ (pericentre of 10 km), and $\Delta a = -3.3$ km per orbit if $e = 0.9$ (pericentre of 5 km). These Δa values refer to the Scenario 2.3.4. For Scenario 2.3.5, Q_g and $|\Delta a|$ increase a factor of 5, and even more in case of models A and B in Keller et al. (2015).

The e decrease can be neglected because $|\Delta e| < 0.01$ per orbit if $e < 0.98$. The chunk orbit collapses on the nucleus in a few orbits if $0.8 < e < 0.98$, as it is always the case (Fulle 1997), predicting a MIRO dust column density slope steeper than −5/3 (Section 2.1) a few months after perihelion. Therefore, most of the chunks entering into bound orbits slowly fall back on the nucleus rather than escape its gravity field, explaining why $f > 80$ per cent.

2.6 Structural nucleus model

Does the 67P erosion of 4 m, in steps of 0.1 m, really sample the nucleus interior? Will the cometary sample-return missions planned in the next few decades be able to sample pristine cometary material? Before answering these questions, we must rely on a nucleus model. The most general approach is to assume that all comet nuclei are made of building blocks. The building blocks may be the pristine cm-sized pebbles building-up planetesimals in the protoplanetary disc (Blum et al. 2017), meter-sized blocks formed by hierarchical accretion and surviving to following collisions (Davidsson et al. 2016), or even bigger blocks reaccreting after catastrophic collisions (Jutzi et al. 2017). In all these cases, above the building-block size the nucleus is statistically homogeneous. What really matters for the nucleus structural models is the macroporosity among the building blocks, predicted by random-packing theory (Fulle & Blum 2017; Blum et al. 2017), covering a tight range centred on 37 per cent. A statistically homogeneous comet nucleus is defined by (Fulle et al. 2016c):

$$\delta = \frac{\rho_D}{c_I \phi_I \rho_I} \tag{8}$$

$$\rho_N = (\rho_D + c_I \phi_I \rho_I)\phi_G = (1 + \delta)\phi_I \phi_G c_I \rho_I \tag{9}$$

$$\rho_D = \phi_D \sum c_i \rho_i = \frac{\delta \rho_N}{(1 + \delta)\phi_G}, \tag{10}$$

where $\rho_N = 538$ kg m^{-3} (Preusker et al. 2017), $\rho_I = 917$ kg m^{-3} (Davidsson et al. 2016) and $\rho_D = 785^{+520}_{-115}$ kg m^{-3} (Fulle et al. 2017; Levasseur-Regourd et al. 2018) are the nucleus, ice and dust average bulk densities; ϕ_D and ϕ_I are the dust and ice microporosity; $\phi_G = 0.63 \pm 0.05$ is the volume filling factor among the building blocks (Fulle & Blum 2017); c_I and c_i are the ice and the refractory volume abundances ($c_I + \sum c_i = 1$); ρ_i are the specific weights of the minerals and organics (nucleus refractories); and δ is the average refractory-to-ice mass ratio inside the nucleus. According to Statement 2.3.2, the dust is assumed to have $c_I = 0$ in equation (10). This is more general than the models based on ternary analyses (Kofman et al. 2015; Pätzold et al. 2016; Herique et al. 2016), which necessarily introduce a bias in the parameter values, implicitly assumed to be inter-dependent.

The dust bulk density reported above has been measured by GIADA over 271 samples collected during the whole Rosetta mission. Models of the dust aggregates collected by COSIMA (Kissel et al. 2007) suggest a lower value (Hornung et al. 2016). The dust bursts observed by OSIRIS close to Rosetta evidenced that COSIMA's lower dust bulk density is affected by a large bias, sampling only the dust aggregates fragile and porous enough to fragment at impact with Rosetta (Fulle et al. 2018; Levasseur-Regourd et al. 2018). GIADA is not affected by such a bias, being sensitive also to aggregates of sulphides and silicates with no microporosity, so that equation (10) constrains the refractory-to-ice mass ratio inside 67P:

$$\delta = \left[\frac{\rho_N}{\phi_G \rho_D} - 1\right]^{-1}, \tag{11}$$

Equation (11) provides the average $\delta \approx 10$, but it is very sensitive to ϕ_G and ρ_D uncertainties, so the 1-σ error affecting ϕ_G and ρ_D provides the range $3 < \delta < \infty$, in agreement with the results discussed in Section 2.4 (Tables 2–5). Equation (11) provides the refractory-to-ice mass ratio inside the nucleus and takes into account an ice mass fraction of 20 per cent for supervolatiles (not taken into account for the chunks, Section 2.1). This explains why the lower limit of δ is 3 and not 4.3 as in Tables 2–5, higher because the absence of chunk supervolatiles and their dehydrated cm-thick crust at the ejection (Table 1).

2.7 Nucleus dielectric permittivity

The CONSERT experiment (Kofman et al. 1998, 2007) probed the 67P head in the vicinity of Abydos down to a depth of about 100 m and measured an average dielectric permittivity $\varepsilon = 1.27 \pm 0.05$, showing a highly porous nucleus (Kofman et al. 2015). Measurement retrieval in term of composition (Herique et al. 2016) shows an organic-rich nucleus with at least 75 per cent volume fraction of the refractory part constituted of organics (66 per cent mass fraction), which is consistent with surface and coma observations from other Rosetta instruments. With this large fraction of organics, CONSERT indicates a nucleus with an ice volume fraction ranging from 6 per cent to 11 per cent, a refractory volume fraction from 16 per cent to 21 per cent and a porosity from 73 per cent to 76 per cent. Each volume fraction is evaluated for the bulk material without any porosity and independently of the particle or pebble structure. This inversion model assumes a nucleus with a density $\rho = 533 \pm 6$ kg m^{-3} and a refractory-to-ice mass ratio between 2 and 6 (Herique et al. 2016) and then gives a resulting refractory-to-ice mass ratio from 3 to 6: the upper limit equals the input value and cannot be confirmed, while the lower limit deviates from the input and is conclusive. Thus, the CONSERT measurement indicates a nucleus refractory-to-ice mass ratio larger than 3. These conclusions should be refined with laboratory characterization of cometary refractory analogues, trying to provide an upper limit. In all the cases, a large refractory-to-ice mass ratio is required to explain the measured low permittivity: indeed we need materials with low permittivity to fit the measured value and with a high-enough density to have small quantities of them (fig. 6 in (Herique et al. 2016)). It is the case of some organics ($\varepsilon \approx 2$ and $\rho \approx 2 \times 10^3$ kg m^{-3}), it is less the case for silicates ($5 < \varepsilon < 7$ and $\rho \approx 3.5 \times 10^3$ kg m^{-3}) and definitively not the case of water ice ($\varepsilon \approx 3.1$ and $\rho \approx 10^3$ kg m^{-3}).

2.8 Outbursts and landslides

Outbursts may dig deeper than 0.1 m before the dehydrated crust is formed again on the nucleus surface after chunks ejection, but sampling a very local spot of the surface. The computation of the dust-to-gas ratio associated to outbursts depends on a very large number of free parameters that cannot be constrained by observations. This fact was confirmed by 67P outburst modelling, providing a wide range for the dust-to-gas mass ratios: from 0.025 (Grün et al. 2016) to 1600 ± 800 (Agarwal et al. 2017) if water sublimation were driving outbursts. Strong assumptions were necessary to infer the gas loss rate: the outbursting nucleus surface was inferred from topographic changes observed after the outburst (Agarwal et al.

2017); the observed 50 per cent increase of the local gas density in the coma was translated into the same increase of the total gas loss rate from the nucleus (Grün et al. 2016). The latter assumption is inconsistent with the suggested explanation of the outburst in terms of a landslide, which should have exposed a surface area of pure ice equal to 50 per cent of the sunlit nucleus surface times the active area fraction not involved in the outburst. Such a surface is a factor >100 larger than that involved in the observed Aswan landslide (Pajola et al. 2017b). Less than 1 per cent of the local gas loss rate increase is consistent with a >50 per cent increase of the local gas coma density, as shown by gas-dynamical coma codes (Fougere et al. 2016; Marschall et al. 2017; Zakharov et al. 2018b). The lower limit of the dust-to-gas mass ratio provided by outbursts is a factor >100 larger than quoted by (Grün et al. 2016), consistent with the lower limit of the refractory-to-ice mass ratio reported in the previous subsection.

Regarding the Aswan landslide, an albedo increase of a factor >6 was observed in the exposed nucleus material, which implies a larger ice content than on the surrounding surface (Pajola et al. 2017b). How to convert such an albedo increase into a refractory-to-ice mass ratio in the exposed material is still a matter of debate. The average ice content in the 67P surface probed by optical observations, is about 1 per cent (Capaccioni 2015). This percentage is much lower than the chunk ice mass fractions reported in Tables 2–5 (also after having corrected them for the albedo increase) and it is insensitive to the few 'blue' spots covering a negligible fraction of the nucleus surface (Barucci et al. 2016). The volume involved in the Aswan landslide is $(2.2 \pm 0.3) \times 10^4$ m^3 (Pajola et al. 2017b), i.e. about 0.05 per cent of that of the chunks ejected around perihelion: landslides do not provide significant statistics of the nucleus interior.

2.9 Summary of Section 2

After Rosetta, the only way we have to probe the average pristine nucleus refractory-to-ice mass ratio, i.e. at depths >10 m, is by means of fits of the nucleus dielectric permittivity measured by CONSERT and of structural models, providing $\delta > 3$ at 1-σ level (subsections 2.6 and 2.7). The Refractory-to-Ice mass ratio in the perihelion chunks (just after their ejection in steps 0.1 m thick) matches such a lower limit, and it is consistent with all the other Rosetta observations, namely with the dust-to-gas ratio in the lost material, in the outbursts and in the layers exposed by landslides. Values of the refractory-to-ice mass ratio much larger than the dust-to-gas mass ratio (i) are required to explain the low distributed water sources outside the Rosetta orbit (Section 2.3) and (ii) imply that 82 per cent of the material eroded at perihelion from the southern hemisphere falls back onto less outgassing or inactive nucleus surfaces (Section 2.5).

Such a fallout may appear large, but is in fact low. The southern erosion involves an area of about 10 km^2 (Keller et al. 2015), i.e. 1/5 of the total nucleus surface (Preusker et al. 2017), so that the total erosion thickness is 4 m (Section 2.1). Since 82 per cent of this erosion is falling back on the whole nucleus surface (Section 2.5), the average fallout thickness is of 0.8 m only, consistent with the topographic changes observed by OSIRIS (Hu et al. 2017a). Outbound from perihelion and inbound to the next perihelion, most outgassing from the fallouts is spent to self-clean such a meter-thick fallout (Section 2.2). Where the self-cleaning is complete, the erosion of the pristine surface, formerly covered by the fallout, may start. In most cases, it will be not observable because the outgassing is much lower than at perihelion, so that the erosion will be probably <1 m. Where the self-cleaning is incomplete, dust accumulates, at a rate definitely lower than 1 m per orbit. Such a rate is consistent with the erosions and depositions actually observed by OSIRIS in many dust deposits (Hu et al. 2017a). It is also in agreement with the thickness of the northern deposits computed by means of coma fluid-dynamical codes, which is >10 dust monolayers per orbit, i.e. a thickness of ≈0.4 m made of dust <3 cm in size (Lai et al. 2016). Because the back-falling chunks have sizes >0.1 m (Section 2.2), the thickness of the deposits should increase >1 m per orbit, unless (Lai et al. 2016) underestimate the self-cleaning occurring in fallouts and their mass.

The fallout mass depends also on the total nucleus mass loss, i.e. $(9 \pm 6) \times 10^9$ kg per orbit (Godard et al. 2017). Far from perihelion, the water coming from the fallout self-cleaning (Section 2.2) is probably more than that coming from cliffs, so that the gas loss from pristine surfaces for one orbit is well approximated by the nucleus gas loss rate around perihelion times 53 d, and ranges from 6×10^8 kg (Scenario 2.3.4) to 2.6×10^9 kg (Scenario 2.3.5). The total mass ejected in chunks from pristine surfaces along one orbit is 2.0×10^{10} kg (Section 2.4), partly escaping at perihelion, partly outgassing in the coma and partly falling back on the nucleus surface, where it outgasses and ejects dust during the fallout self-cleaning and inbound activity. In order to fit the observed total nucleus mass loss, the fallout accumulating every orbit in the deposits ranges from $(20 + 0.6 - 9) \times 10^9 = 1.16 \times 10^{10}$ kg (Scenario 2.3.4) to $(20 + 2.6 - 9) \times 10^9 = 1.36 \times 10^{10}$ kg (Scenario 2.3.5). According to the classification of the 67P surface, the 'Airfall deposits' and the 'Smooth (changing) surfaces' cover a total surface of 14 km^2 (Thomas et al. 2018), over which the above mentioned masses accumulate every orbit a deposit thickness of 1.8 ± 1.6 m. The thickness uncertainty is due to the 66 per cent uncertainty affecting the total mass lost by the nucleus, and to the 25 per cent uncertainty affecting the chunk loss rate. These deposits are a factor of 2 thicker than the uniform fallout computed above, suggesting that both Godard et al. (2017) and Thomas et al. (2018) underestimate the nucleus mass loss and the permanent deposits surface, respectively, unless the northern fallout is thicker than the average, consistent with the fact that most deposits cover the northern hemisphere. The large thickness uncertainty is consistent with the impossibility of evaluating all possible sources and sinks of gas and dust over the whole 67P orbit, which prevents to estimate the nucleus Refractory-to-Ice mass ratio following such an approach.

These lines of evidence explain why the dust-to-gas mass ratio in the lost material is an order of magnitude lower than the refractory-to-ice mass ratio inside the nucleus (Tables 2 to 5): (i) the lost material is missing more than 80 per cent of the refractory component present in the pristine nucleus, i.e. before ejection; (ii) the ice included in the falling back chunks is <6 per cent of the ejected mass.

3 FLYBYS TO COMETS

3.1 Giotto and Flybys at 1P/Halley, 9P/Tempel 1 and 81P/Wild 2

GIADA data at 67P have shown that the dust flux at terminator or at phase angles $\alpha > 90$ deg is a negligible fraction of the dust flux on the day side, $\alpha < 90$ deg (Della Corte et al. 2015, 2016). This is consistent with fluid-dynamical gas comae codes (Fougere et al. 2016; Marschall et al. 2017; Zakharov et al. 2018b), thus it applies to all comets. This has huge consequences on the interpretation of in-situ dust fluences measured during all the previous cometary missions, i.e. flybys approaching comets at terminator or on the night side, as Giotto at 1P/Halley (1P hereinafter, flyby at 68.4 km s^{-1} and $\alpha = 107$ deg (Levasseur-Regourd et al. 1999)). Contrary to Giotto, Rosetta was orbiting 67P at speed orders of magnitude lower than the dust velocity (Della Corte et al. 2016). For the instruments onboard Rosetta having field of views (FOVs) of less than a steradian, the observations of any dust particle reflected by the solar radiation pressure can be excluded (sun-pointing GIADA microbalances were anyway monitoring such flux (Della Corte et al. 2015)). Since all the dust particles (either detected by nadir-pointing instruments with limited FOV, or observed in radial motion by OSIRIS) were surely those directly coming from the nucleus, a simple model, considering spherical expansion of the dust coma in the sun-faced hemisphere, provided reliable estimates of the dust loss rate (Fulle et al. 2016a; Ott et al. 2017). The opposite was for Giotto: the high spacecraft speed forced the detection of both direct and reflected particles all coming from the same direction, with a flux dominated by the reflected particles, because of the flyby geometry.

It follows that a simple isotropic model applied to interpret the observed fluence in terms of the dust size distribution at the nucleus surface introduces a large bias in the ejected dust mass as well as in the shape and slope of the dust size distribution (Fulle et al. 1995, 2000). This explains why dust fluences measured during flybys have the typical 'DIDSY shape' (McDonnell et al. 1989, 1993; Green et al. 2004; Tuzzolino et al. 2004; Economou et al. 2013), i.e. a much shallower slope for masses between 10^{-9} and 10^{-7} kg than outside this mass range. They are all affected by the same dynamical artefact (Fulle et al. 1995) and are always consistent with a power law index constant over the whole observed mass ranges. This bias affects also the dust-to-gas ratio, which was estimated close to 2 in 1P by means of isotropic models (McDonnell et al. 1989). Modelling the DIDSY dust fluence in terms of a realistic anisotropic dust ejection, i.e. much larger at subsolar nucleus surface than at terminator (thus disentangling the contribution of direct versus reflected particles), it becomes a power law with a differential power index of -2.6 ± 0.2 (Fulle et al. 2000). This implies the dust-to-gas mass ratio ranging from 3 to 40 for dust masses <0.3 g (Fulle et al. 2000), much larger than the dust-to-gas mass ratios in the lost material observed in 67P (last rows of Tables 2–5). 1P shares this property with Comet Hale-Bopp, with a dust-to-gas mass ratio >5 in the lost material (Jewitt & Matthews 1999), matching the results of the analyses of the data collected during the 9P/Tempel 1 flyby (Küppers et al. 2005; Jorda et al. 2007).

3.2 EPOXI at 103P/Hartley 2

103P coma models show that most of its ejected water vapour is coming from distributed water sources, i.e. the chunks in the coma, which may have a low ice mass fraction and sizes >1 m, consistent with the observed distributed water sources (Kelley et al. 2015). The 103P nucleus volume is a factor 30 smaller than 67P (Thomas et al. 2013), so that a gas surface density similar to that of 67P can eject chunks larger than 67P once out of the nucleus gravity field. Taking into account the dust velocity determined by radar observations (Harmon et al. 2011), the chunk ejection rate observed by EPOXI becomes $Q_{RC} + Q_{IC} \approx 10^4$ kg s^{-1} (Kelley et al. 2015), with the dust-to-gas mass ratio of ≈50 (Kelley et al. 2015), taking into account the CO_2 loss rate of ≈160 kg s^{-1}. In order to make consistent $Q_{RC} + Q_{IC}$ with the observed radar cross section, most of the chunks must disappear outside the EPOXI field of view of 21 km (Kelley et al. 2015). This is naturally explained by the chunk fallout on the 103P nucleus (similar to the 67P one), whereas the invoked chunk fragmentation into pieces too small to be detected by the radar (Kelley et al. 2013) is not supported by IR tail observations Epifani et al. (2001). The 103P chunk size distribution has a differential power index of −4.7 between 0.1 and 10 m (Kelley et al. 2013), even steeper than that of 67P above 25 cm (Pajola et al. 2017a), consistent with the strong peak at 1 kg of the chunk cross-section and mass distributions observed in 67P.

The vapour loss rate provided by Lyman-α data is 270 kg s^{-1} at EPOXI flyby (Combi et al. 2011). 103P coma fluid-dynamical codes provided a water loss rate from the nucleus of 60 kg s^{-1} (Fougere et al. 2013), thus fixing that from the chunks at $Q_{WC} = 210$ kg s^{-1}. The nucleus gas ejection is modeled with 3×10^{-5} kg m^{-2} s^{-1} of water from the dust deposits, and with 4×10^{-5} kg m^{-2} s^{-1} of CO_2 and $Q_g = 10^{-5}$ kg m^{-2} s^{-1} of water from the subsolar surface (Fougere et al. 2013), probably ejecting the chunks. 103P and 67P seem to dehydrate similar chunks at a similar rate Q_g (Table 1), thus suggesting similar Q_{WC} values. 103P belongs to the family of hyperactive comets, i.e. the total water loss rate requires a nucleus active area fraction slightly >100 per cent. This is clearly due to distributed water sources from the chunks (Kelley et al. 2015). The effective nucleus active area fraction can be recovered when we divide it by the factor

$$F = \frac{\sigma_D}{\sigma_N} = \frac{R A f \rho}{2 A_p \sigma_N}, \tag{12}$$

where σ_N and σ_D are the total cross sections of the nucleus and of the dust in the coma within the nucleus distance R, and $A_p \approx$ 5 per cent is the dust geometric albedo. At $R \approx 10^4$ km, $Af\rho \approx$ 4 m (Moreno et al. 2017) for 67P and $Af\rho \approx 1.3$ m (Milani et al. 2013; Pozuelos et al. 2014) for 103P provide $F_{103P}/F_{67P} \approx 10$. At perihelion, the active area fraction of 103P becomes just a factor 2 larger than 67P, thus making the Refractory-to-Ice mass ratio of 67P consistent also with that of 103P. Actually, the only difference between the two comets is their total nucleus surface, with a ratio of ten (Thomas et al. 2013; Preusker et al. 2017), matching the ratio between the 67P and 103P gas loss rates from the nucleus. The dust and gas dynamics in 67P and 103P comae are similar, driven by similar gas expanding speeds. Therefore, the ratio between the gas loss rate from distributed water sources and that from the nucleus should be ten times lower in 67P than in 103P, i.e. 1/3 (1/4 of gas from 67P distributed sources and 3/4 from the 67P nucleus). In this case, $Q_{WC} = 165$ kg s^{-1} in 67P (Tables 6 and 7), with the refractory-to-ice mass ratios inside the nucleus of 7 and 14 (Table 1), closer to the average given by equation (11).

Since 103P IR tail models provide $Q_D = 90 \pm 20$ kg s^{-1} (Epifani et al. 2001; Pozuelos et al. 2014), the fallout mass is $f \approx 99$ per cent if $Q_L \approx Q_D$. Taking into account both 103P CO_2 and water loss rates per unit area (Fougere et al. 2013), Q_g in equation (6) is a factor of 5 larger than in 67P. In 103P, probably $a < 20$ km, so that equation (6) provides values of $|\Delta a/a|$ much larger than in 67P, consistent with $f \gg 80$ per cent. An estimate of the refractory-to-ice mass ratio inside 103P by means of equations (2) and (3) is not constrained by the available 103P data. Just as an example, we assume the same ice mass fraction $Z_C \approx 25$ per cent both in the pristine nucleus surface and in the deposits. $Z_C \approx 25$ per cent (being a lower limit of the active area fraction (Hu et al. 2017b) if the 103P nucleus is homogeneous) provides a total active area fraction >100 per cent when multiplied by 4.5, i.e. the ratio between the total and the nucleus vapour loss rates. These values of f and Z_C make $Z_C Q_D$ consistent with the 103P total water loss rate. The dust-to-gas mass ratio in the lost material becomes 0.33 (Table 8), i.e. 167 at the sunward erosion (0.2 and ≈50 taking into account the CO_2 loss rate (Kelley et al. 2015)).

Table 6. Refractory-to-ice ratio vs. dust-to-gas ratio in 67P: Hapi's active area fraction = 7.5%, 103P-scaled distributed water sources, $\rho_C = 515$ kg m^{-3}, $f = 92\%$. In the last column, the loss rate of 260 kg s^{-1} of dust of mass <10 g is taken into account.

Physical process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Gas rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Southern erosion	3965	485	495		9.5 = (4450 + 260) / 495
Into chunks at ejection	3965	485		8.2 (11.%)	
Into gas from chunks			165		
Into fallout	3780	305		12. (7.5%)	
Into lost material	185	15	660	12. (7.5%)	0.7 = (200 + 260) / 660

Table 7. Refractory-to-ice ratio vs. dust-to-gas ratio in 67P: Hapi's active area fraction = 1.2%, 103P-scaled distributed water sources, $\rho_C = 515$ kg m^{-3}, $f = 92\%$. In the last column, the loss rate of 260 kg s^{-1} of dust of mass <10 g is taken into account.

Physical process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Gas rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Southern erosion	4230	220	495		9.5 = (4450 + 260) / 495
Into chunks at ejection	4230	220		19. (4.9%)	
Into gas from chunks			165		
Into fallout	4032	53		80. (1.2%)	
Into lost material	198	2	660	80. (1.2%)	0.7 = (200 + 260) / 660

This corresponds to a refractory-to-ice mass ratio of 3 inside 103P, matching the 67P lower limit, and a factor of ten larger than the dust-to-gas mass ratio in the lost material.

4 GROUND-BASED OBSERVATIONS

Observations from ground-based telescopes and Earth-bound satellites range from optical and near-IR observations of the dust coma and tail, mainly sensistive to sub-mm-sized dust particles (Fulle 2004), up to radar observations, mainly sensitive to meter-sized chunks (Harmon et al. 2004). In general, the former provide dust-to-gas ratio values which are strong underestimates, apart from tail models properly extrapolated to sizes larger than some cm (Moreno et al. 2017). Trails of Jupiter-family comets are mainly composed of mm-cm-sized particles, and thus provide better estimates of the dust-to-gas mass ratios in the lost material, often ranging from 1 to 5 (Sykes et al. 2004). Trails are depleted of the largest ejected and falling back chunks, so that the dust size distribution extracted by trail models has always a bias at the largest sizes, i.e. it is always steeper than the real one at the ejection, as confirmed in 67P (Section 2.4).

Radar observations often provide much larger dust masses than contemporaneous tail and trail models (Harmon et al. 2004, 2011), evidencing the dominant chunk fallout on nuclei, due to mass conservation of any chunk fragmentation into smaller dust composing the tails and trails. The size of the chunks measured in-situ at 67P and 103P inner comae is always larger than the radar wavelength divided by 2π, so that the proper radar scattering regime describing the chunk coma is the geometric one. If >80 per cent of the chunks fall back on the nucleus after having reached the average nucleus distance R_C, the radar signal is given by the outflow and the inflow of the chunks occurring at similar average radial velocity V_r inside R_C, which is much smaller than the radar beam size. Therefore, the chunk mass ejection rate is

$$Q_{RC} + Q_{IC} = \frac{V_r \sigma_r S_C \rho_C}{3 R_C}, \qquad (13)$$

where V_r and σ_r are the chunk dispersion speed and cross-section provided by radar observations (Harmon et al. 2004); S_C and $\rho_C = 538$ kg m^{-3} are the chunk diameter and bulk density, respectively. $Q_{RC} + Q_{IC}$ measures the dust-to-gas mass ratio at the erosion (Subsec 2.4 and first row in Tables 2–8), to be compared to the dust-to-gas mass ratio in the lost material (last rows in Tables 2 to 8), provided by the total mass lost by the nucleus, by tail and trail models, and by the flyby fluences measured in the coma.

For 1P, $V_r = 2.65$ m s^{-1} and $\sigma_r = 32$ km^2 (Harmon et al. 2004). V_r is consistent with the escape speed from 1P nucleus, suggesting chunks in bound orbits much smaller than in 67P. The gas loss rate during the Giotto flyby was 2×10^4 kg s^{-1} (Krankowsky et al. 1986). In order to fit the dust-to-gas mass ratio >15, best fitting the coma optical flux measured by the Optical Probe Experiment (Levasseur-Regourd et al. 1999) and the DIDSY dust flux (Section 3.1), multiplied by a factor of 5 to get the 80 per cent fallout, the mass ejection rate of the chunks (assumed here similar to 67P ones) must be $Q_{RC} + Q_{IC} > 3 \times 10^5$ kg s^{-1}, providing $R_C < 20$ km. This is consistent with the computations of the bound orbits around the 1P nucleus during the Giotto flyby (Fulle 1997) (at aphelion, R_C can be a factor of 50 larger). Models of the 1P dust tail were sampling much smaller dust and providing a dust-to-gas mass ratio close to 1/4 (Fulle, Barbieri & Cremonese 1988).

In case of 103P, $V_r = 4$ m s^{-1} and $\sigma_r = 0.89$ km^2 (Harmon et al. 2011). EPOXI data provide a similar total chunk cross section inside the EPOXI field of view $R_C = 20.6$ km (Kelley et al. 2015). Thus the estimated chunk loss rate $Q_{RC} + Q_{IC} \approx 10^4$ kg s^{-1}, consistent with V_r (Kelley et al. 2015), provides $S_C \approx 0.3$ m, confirming that 103P chunks had sizes similar to those observed in 67P and were mostly falling back ($f \approx 99$ per cent in Table 8). The actually observed outgassing of chunks ejected sunward may decelerate them from V_r to velocities lower than the escape speed (Agarwal et al. 2016), consistent with the sharp peak of the radar signal. The wings of the radar bandwith may be due to the fraction of escaping chunks and smaller particles. The chunk ejection rate $Q_{RC} + Q_{IC}$ is orders of magnitude larger than the dust loss rate observed in the IR dust tail, 90 ± 20 kg s^{-1} (Epifani et al. 2001), which samples dust particles

Table 8. Refractory-to-ice ratio vs. dust-to-gas ratio in 103P: Nucleus ice mass fraction ≈25%, $f \approx 99\%$.

Physical process	Refractory rate kg s^{-1}	Ice rate kg s^{-1}	Vapour rate kg s^{-1}	Refractory-to-ice mass ratio (ice mass fraction in %)	Dust-to-gas mass ratio (Dust = Refractory + Ice)
Sunward erosion	7500	2500	60		167.
Into coma chunks	7500	2500		3.0 (25%)	
Into gas from chunks			210		
Into fallout	7430	2270		3.3 (23%)	
Into lost material	70	20	270	3.5 (22%)	0.33

of sizes smaller than 1 cm. The faint IR dust tail evidences that the chunks are not fragmented into smaller dust, well monitored by tail and trail models: they can only disappear falling back on the nucleus.

These two examples show that, among ground-based observations, only radar observations coupled to water-gas measurements may provide, by means of equation (13), reliable estimates of the dust-to-gas mass ratio at the erosion. Even if it is always much larger than that sampled in the lost material, it can be anyway lower than the refractory-to-ice mass ratio inside the nucleus. Radar observations provide reliable estimates of the nucleus size, which allows us to infer the S_C and R_C values in equation (13).

All the dust-to-gas mass ratios at the erosion obtained so far (Tables 2 to 8) confirm that the refractory-to-ice mass ratio ≥3 probably characterizes all comets. There is no evidence that the outgassing from splitting comets increases by a factor larger than the increase of the sunlit nucleus surface after nucleus fragmentation. This implies that the nucleus surface active area fraction is similar to the inner nucleus one. It is also challenging to prove that comets split into nuclei all small enough to prevent any fallout due to their negligible gravity field. Only in this case the dust-to-gas ratio in the lost material corresponds to the refractory-to-ice mass ratio inside the nucleus.

5 KUIPER BELT OBJECTS

Kuiper Belt Objects (KBOs hereinafter) are not comets. However, according to the collisional models of comet formation (Rickman et al. 2015), comets may be fragments of KBOs. Following other formation scenarios, comets and KBOs formed in the same outer regions of the protoplanetary disc (Blum et al. 2017), so that they should have the same average refractory-to-ice mass ratios. Equations (8) to (11) can be applied to all KBOs with sizes <100 km, where the lithostatic pressure and melting are negligible (Blum et al. 2017; Fulle & Blum 2017). Unfortunately, data on the bulk density of KBO's smaller than 100 km, not yet visited by spacecrafts, are unreliable (Brown 2013) as recently shown by Haumea observations (Ortiz et al. 2017). Stellar occultation data have updated the size from 1300 to 1600 km, the geometric albedo from (75 ± 6) per cent to (51 ± 2) per cent, and the bulk density from 2600 to 1820 kg m^{-3} (Brown 2013; Ortiz et al. 2017). Thermal data of KBOs are affected by uncertainties larger than estimated. The bulk density depends strongly on the object shape, and the usually assumed spherical shape maximizes the volume-to-cross-section ratio. We here consider the only well-established bulk densities of four KBOs, namely Charon, Haumea, Pluto and Triton, for which the lithostatic pressure and differentiation by melting compressed the bodies to zero porosity. In this case, equations (8) to (11) become (Fulle 2017)

$$\rho_K = \sum c_i \rho_i + \left(1 - \sum c_i\right) \rho_I = c_1 \rho_5 + (1 - c_1/c_5)\rho_I \qquad (14)$$

$$\rho_5 = \rho_1 + (c_2/c_1)\rho_2 + (c_3/c_1)\rho_3 \qquad (15)$$

$$c_5 = [1 + c_2/c_1 + c_3/c_1]^{-1} \qquad (16)$$

$$\delta = \frac{c_1 \rho_5}{(1 - c_1/c_5)\rho_I} = \frac{\frac{\rho_K}{\rho_I} - 1}{1 - \frac{\rho_K}{c_5 \rho_5}}. \qquad (17)$$

This allows us to relate the KBO bulk density, ρ_K, to the ratios of the volume abundances of silicates, c_2, and of hydrocarbons, c_3, to that of sulphides, c_1 (Fulle 2017): $c_2/c_1 = 4$ and $c_2/c_1 = 5$ for CI-chondritic and solar compositions, respectively; $c_3/c_1 = 6$ and $c_3/c_1 = 7$ for CI-chondritic compositions (and either amorphous or crystalline ice) at KBO formation, respectively; and $c_3/c_1 = 12$ and $c_3/c_1 = 14$ for solar compositions (and either amorphous or crystalline ice) at KBO formation, respectively (Fulle et al. 2016c). In comets and KBOs, the bulk densities of sulphides and silicates, namely $\rho_1 = 4600$ kg m^{-3} and $\rho_2 = 3200$ kg m^{-3}, are less controversial than that of hydrocarbons. Soft hydrogenated carbon alloys have $\rho_3 \approx 1200$ kg m^{-3} (Robertson 2002). The organic component of the 67P dust has a composition very close to the Insoluble Organic Matter (IOM hereinafter) found in CI-chondrites (Fray et al. 2016; Bardyn et al. 2017; Levasseur-Regourd et al. 2018), i.e. a disordered assemblage of Carbon and Hydrogen rings and chains with impurities of Oxygen and, to a lesser extent, Nitrogen (the 1P/Halley CHON particles, (Jessberger, Christoforidis & Kissel 1988)). The best terrestrial analogues (not dealing with origin) of IOM are kerogens (Nakamura 2005). The bulk density of kerogens drifts from values of 950 kg m^{-3}, for young deposits very enriched in Hydrogen, to values of 1450 kg m^{-3}, for old deposits, depleted in Hydrogen. Typical values for the kerogens bulk density are $\rho_3 = 1210 \pm 40$ kg m^{-3} (Oklongbo, Aplin & Larter 2005), in agreement with $\rho_3 = 1200$ kg m^{-3} (Fulle 2017).

The values of the refractory-to-ice mass ratio provided by equation (17) for Charon, Haumea, Pluto and Triton are reported in Table 9 for the end-cases of CI-chondritic and solar compositions. They further confirm what has been found for 67P, i.e. $3 < \delta < \infty$. A size-density trend of KBOs has been suggested and interpreted in terms of KBO porosity (Brown 2013). This would imply that Triton only may provide a significant refractory-to-ice mass ratio, with a composition of all KBOs inconsistent with the solar end-case. In differentiated KBOs, a significant porosity is impossible, so that such a size-density correlation is probably an observational bias.

6 CONCLUSIONS

Rosetta allowed us to understand how complex the relationship is that links the dust-to-gas mass ratio in the lost material to the refractory-to-ice mass ratio, δ, inside a comet nucleus, the latter

Table 9. Refractory-to-ice mass ratios of KBOs (from equation (17)).

KBO	Amorphous Ice CI-chondritic	Crystalline Ice CI-chondritic	Amorphous Ice Solar end-case	Crystalline Ice Solar end-case
Charon	3.6	4.1	6.8	9.4
Haumea	5.3	6.4	15.	37.
Pluto	6.1	7.6	24.	192.
Triton	16.	30.	∞	∞

being the parameter really constraining the origin of comets and KBOs. We evidenced the fundamental influence of dust transfer in determining δ: chunks ejected from surface areas dominated by the perihelion erosion falling back to different nucleus regions where dust deposits may accumulate. This transfer involves >80 per cent of the ejected mass, and increases δ inside the nucleus by a factor 6 ± 3 with respect to the dust-to-gas mass ratio in the lost material, because the lost material is depleted by >80 per cent of the refractory mass that was inside the pristine nucleus before its ejection. Since the lost material is strongly enriched in gas when compared to the nucleus ice content, the nucleus mass loss (of about 0.1 per cent per orbit) introduces a slow time variation of the average nucleus δ, which increases its value by <10 per cent after 100 orbits in the inner Solar System. In case of a nucleus with a stable spin like 67P, this time drift will concern the northern hemisphere only, whereas the erosion will maintain pristine δ in the southern hemisphere. All data we have on comets provide a similar constraint on the pristine δ inside comets and KBOs, i.e. $\delta > 3$. This may make comets and KBOs less rich in water than CI-chondrites, which have a refractory-to-water mass ratio close to 5.5 (Marty et al. 2016) and the water included in minerals, which is not the case for the 67P dust (Schulz et al. 2015). This constraint confirms that comets can be defined as 'mineral organices' (Fulle et al. 2016b), i.e. a mixture of minerals and organics with a minor mass fraction of ices mixed among them, and provides a disentangling test for all models describing the (probably common) origin of comets and KBOs. For instance, streaming instability models explain comets as born from the gentle gravitational collapse of cm-sized pebbles (Blum et al. 2017), in which case $3 < \delta < 9$ (Lorek et al. 2016). Such a striking agreement with all actual data on δ may suggest that we understand the origin of comets better than their activity.

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