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Version: Version of Record

Link(s) to article on publisher’s website:
http://dx.doi.org/doi:10.1093/mnras/stx983

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The dust-to-ices ratio in comets and Kuiper belt objects

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Accepted 2017 April 21. Received 2017 March 27; in original form 2017 January 4

ABSTRACT
Comet 67P/Churyumov-Gerasimenko (67P hereinafter) is characterized by a dust transfer from the southern hemi-nucleus to the night-side northern dust deposits, which constrains the dust-to-ices mass ratio inside the nucleus to values a factor of 2 larger than that provided by the lost mass of gas and non-volatiles. This applies to all comets because the gas density in all night comae cannot prevent the dust fallback. Taking into account Grain Impact Analyser and Dust Accumulator (GIADA) data collected during the entire Rosetta mission, we update the average dust bulk density to \( \rho_D = 785^{+520}_{-115} \) kg m\(^{-3}\) that, coupled to the 67P nucleus bulk density, confirms an average dust-to-ices mass ratio \( \delta = 7.5 \) inside 67P. The improved dust densities are consistent with a mixture of (20 ± 8) per cent of ices, (4 ± 1) per cent of Fe sulphides, (22 ± 2) per cent of silicates and (54 ± 5) per cent of hydrocarbons, on average volume abundances. These values correspond to solar chemical abundances, as suggested by the elemental C/Fe ratio observed in 67P. The ice content in 67P matches that inferred in Kuiper belt objects, (20 ± 12) per cent on average volume abundance and suggests a water content in all trans-Neptunian objects lower than in CI chondrites. The 67P icy pebbles and the dust collected by GIADA have a microporosity of (49 ± 5) and (59 ± 8) per cent, respectively.


1 INTRODUCTION
While ground-based coma observations provide reliable measurements of the water loss rate, unrealistic assumptions of the dust size distribution have often provided strong underestimates of the dust loss rate from comets (Newburn & Spinrad 1985), with the consequence that the dust-to-ices mass ratio \( \delta \) has been often assumed <1. Here, with dust we refer to the total non-volatile component of a comet nucleus. Often, the dust size distribution was assumed very steep, with both the dust mass and optical brightness dependent on micron-sized particles, opposite to what has been observed with Rosetta, with the 67P dust mass dependent on the largest ejected chunks and the optical brightness on mm-sized particles (Rotundi et al. 2015; Fulle et al. 2016a). For example, Kresak & Kresakova (1987) provided the loss rates from most Jupiter-family comets (JFCs hereinafter) assuming \( \delta = 1/3 \). In 67P, Kresak & Kresakova (1987) estimated a water loss rate per orbit about 20 per cent larger than actual measurements (Bertaux 2015; Shinnaka et al. 2017). The Giotto mission to comet 1P/Halley showed that \( \delta > 1 \) and a more recent analysis of the Giotto dust data provided \( 3 < \delta < 40 \) (Fulle et al. 2000). This result confirmed the \( \delta \) estimates for JFCs (Sykes & Walker 1992a) based on the first ground-based observations able to infer reliable dust mass loss rates, derived by models of the IRAS dust trails (Sykes & Walker 1992b). Regarding 67P, Sykes & Walker (1992a) found \( \delta = 4.6 \), a good prediction of the values later confirmed by the Rosetta mission in the material lost by the comet, \( \delta = 4 \pm 2 \) (Rotundi et al. 2015). In the same paper, Sykes & Walker (1992a) showed that the low bulk density of Pluto and Triton is consistent with the same volume abundances of dust...
in the coma and the deposits has the same water mass fraction as the dust mass involved in the day-to-night dust transfer. The dust to the sun.

Thick deposits, which are eroded once the night surface is exposed to daylight. The day-to-night dust transfer is probably very similar in all comets because the nucleus surface temperature on the night side, and therefore the gas outflow, is similarly low in all comets. Thus, the cut-off dust mass, below which the fall-back on the night side nucleus surface most efficient (Fulle et al. 2016b). A stable spin axis is a necessary condition to cumulate thick deposits on the northern hemisphere (Keller et al. 2015b). The coherent orientation of tail-like structures observed during the Rosetta period, Hansen et al. (2016) estimate a water loss of \(6.4 \times 10^{28}\) mol s\(^{-1}\) from the total water mass \(ZM_a\) (Shinnaka et al. 2017) and \(M_a\) is 3 \(\times\) \(10^9\) kg is the dust mass in particles of mass >1 mg. \(M_a\) has been computed inside the Rosetta orbit of radius \(R \approx 400\) km, where the mass in dust particles is \(R Q_{m}/v\) in the case of a spherical expansion at constant speed \(v\). The mass loss rate \(Q_{m}\) and \(v\) are provided by Optical, Spectroscopic, and Infrared Remote Imaging System data (Fulle et al. 2016a). Actually, the mass in particles is larger due to the dust acceleration from the nucleus surface to the distance \(R\). Particles reaching a nucleus distance larger than \(R\) have a negligible probability to fall back into the deposits. The day-to-night transfer lasts much less than \(ZM_a/c Q_w > 8\) d on average, supporting the assumption of the same \(Z\) in the dust deposits and in the coma dust.

Radio Science Investigation (RSI) onboard Rosetta measures a total mass loss from 67P nucleus of \((1.1 \pm 0.3) \times 10^{10}\) kg from August 2014 to September 2016 (Pätzold et al. 2016). During the same period, Hansen et al. (2016) estimate a water loss of \(6.4 \times 10^{28}\) kg by modelling Rosetta in situ data, with a maximum water loss rate of \((3.5 \pm 0.5) \times 10^{28}\) mol s\(^{-1}\), a factor of 3 larger than provided by Earth-orbiting satellites, (1.3 \(\pm\) 0.15) \(\times\) \(10^{28}\) mol s\(^{-1}\) (Shinnaka et al. 2017). This is inconsistent with, e.g. water-distributed sources, which imply in situ measurements of the water loss rate lower than Earth-based ones. Such a systematic error of the water loss rate estimated by Hansen et al. (2016) at perihelion is confirmed by the overestimate by a factor of 4 of the IR water flux modelled by Hansen et al. (2016) and Fougere et al. (2016) with respect to that measured by Visible and Infrared Thermal Imaging Spectrometer (VIRTIS; Bockelée-Morvan et al. 2016), which makes VIRTIS data consistent with Earth-based ones (Bertaux 2015; Shinnaka et al. 2017) and with the water loss rate fitting the acceleration of the 67P nucleus spin (Keller et al. 2015a). Taking into account the systematic correction of the total water loss provided by Hansen et al. (2016), it becomes consistent with previous estimates of \(2.7 \times 10^{10}\) kg (Bertaux 2015; Keller et al. 2015b), so that the RSI measurements provide \(\delta_{\text{water}} \geq 3 \pm 1\), again significantly lower than \(\delta_{\text{water}} \approx 8\) provided by equations (1) and (2). This difference
measures the dust mass involved in the day-to-night transfer. If $\delta_{\text{water}}$ inside the nucleus were exactly that inferred for the lost material, the dust mass deposited on the night side would be exactly zero, according to the assumption that all the dust is lost in space. Instead, to obtain dust deposits, $\delta_{\text{water}}$ inside the nucleus has to be significantly larger than the values observed in the lost material. In 67P, if the lost material has $\delta_{\text{water}} = 3$ and the nucleus pristine material has $\delta_{\text{water}} = 8$, i.e. 16 dust unit masses and 2 water unit masses, then 1 water unit mass is lost in space and another remains on the surface together with 13 dust unit masses, so that the dehydrated material remaining on the nucleus surface has a water mass fraction of 7 per cent, in good agreement with the water mass fraction $Z = 5\pm 3$ per cent of 67P ices are composed of CO, CO$_2$ and O$_2$ (Fulle et al. 2016c) and the lower limits for porous ices. The volume abundance of water inside the nucleus has to be significantly larger than the values observed in the lost material.

\[ \delta = \left( \frac{\rho_N}{\phi_0 \rho_D} - 1 \right)^{-1}, \]

where $\rho_N = 533$ kg m$^{-3}$ is the 67P nucleus bulk density and $1 - \phi_0 = 0.4$ is the nucleus macro-porosity (Fulle et al. 2016c). With $\rho_D = 785$ kg m$^{-3}$, we get $\delta = 7.5$ on average, consistent with $\delta_{\text{water}} \approx 8$ discussed in the previous section because at least 10 per cent of 67P ices are composed of CO, CO$_2$ and O$_2$ (Fulle et al. 2016b). The lower and upper limits $\rho_D = 670$ kg m$^{-3}$ and $\rho_D = 1300$ kg m$^{-3}$ provide $\delta = 3.1$ and $\delta = \infty$, respectively. The 67P C/Fe ratio (Fray et al. 2016) is close to the solar end-case (Lodders 2003), so that the updated $\delta = 7.5$ and the solar elemental abundances constrain the free parameters of the structural equations of the 67P nucleus plotted in Figs 2 and 3 of Fulle et al. (2016c), namely the microporosity and the volume abundances $c_1 = (4 \pm 1)$ per cent of Fe sulphides (bulk density $\rho_1 = 4600$ kg m$^{-3}$), $c_2 = (22 \pm 2)$ per cent of silicates ($\rho_2 = 3200$ kg m$^{-3}$ for Mg, Fe olivines and pyroxenes, $\rho_3 = 2600$ kg m$^{-3}$ for amorphous silicates; Fulle et al. 2016c) and $c_3 = (54 \pm 5)$ per cent of hydrocarbons ($\rho_3 = 1200$ kg m$^{-3}$; Robertson 2002). The upper limits are obtained for compact ices and the lower limits for porous ices. The volume abundance of

\[ \rho = \frac{C}{G D N}, \]

where $D$ is linked to the non-volatiles-to-ices mass ratio inside the nucleus

\[ D = \frac{C}{G D N} \]

Figure 1. Mass and cross-section $\chi$ measurements of compact particles detected by GIADA from August 2014 to September 2016 (the error bars refer to $1 - \sigma$ standard error of the 271 GDS+IS measurements). The data are compared with the trends of prolate and oblate ellipsoids of aspect ratio of 10 (dotted lines) and 5 (dashed lines), respectively, and with dust bulk densities of Fe sulphides, $\rho_1 = 4600$ kg m$^{-3}$ (upper lines), and of hydrocarbons, $\rho_3 = 1200$ kg m$^{-3}$ (lower lines). Particles located below the lower lines have a high porosity. The GDS signal saturates at $\chi > 10^{-6}$ m$^2$. Particles with $\chi < 2 \times 10^{-8}$ m$^2$ (and most of those with mass $< 10^{-8}$ kg) were too small and fast to be detected by GDS. The flux at masses $> 2 \times 10^{-9}$ kg was very low during the entire mission due to the spacecraft safety constraints.
ices in 67P is $c_2 = (20 \pm 8)$ per cent, with the upper limit corresponding to porous ices. This value matches the volume abundances of ices found in 10 parameter combinations valid for KBOs (between the end-cases of solar and CI-chondritic compositions), $c_2 = (20 \pm 12)$ per cent (Fulle 2017). The updated microporosity of the pebbles, i.e. the icy building-blocks of the 67P nucleus, is $1 - \phi = (49 \pm 5)$ per cent. The dust microporosity is $1 - (1 - c_1)\phi = (59 \pm 8)$ per cent, where the factor $(1 - c_1)$ takes into account the voids left in the dust by the ices after sublimation. The bulk density of compacted dust becomes $\rho_{\text{D}}/[1 - c_1] = 1925 \pm 2030$ kg m$^{-3}$. The upper limits of the microporosities and of the compacted bulk density are obtained for crystalline silicates and compact ices, the lower limits for amorphous silicates and porous ices.

4 DISCUSSION

Both 67P and KBOs contain only one-fifth of their volume as ice, thus less water than CI-chondrites (McKinnon et al. 1997). This suggests that bodies born close to the water snowline contain more water than TNOs. This is consistent with the D/H ratios in 67P, i.e. closer to the CI-chondritic end-case, C/Fe = 12 (Jessberger et al. 1989), even larger than the solar one. Comets may also have a CI-chondritic C/Fe ratio, as it is confirmed by Stardust data and by KBOs. The composition of dust from comet 81P/Wild 2 is CI-chondritic, although the actual carbon bias on the data is unknown (Brownlee 2014). Fulle (2017) showed that Triton’s bulk density is consistent with a CI-chondritic composition, not with a solar one. Fray et al. (2016) found that the 67P C/Fe ratio is close to the solar end-case, although the bias in the detections of 67P’s C, Si, and Fe remains unknown. In this case, the 67P ratios $h/s = (c_1\rho_3)/(c_2\rho_2), c_2/c_1 = 5, c_3/c_1 = 12$ for porous ices and $c_1/c_1 = 14$ for compact ices match the values assumed to compute the KBO composition (Fulle 2017), and fix the largest possible KBO bulk density $c_3\rho_3$, where $c_3 = (1 + c_1/c_1 + c_2/c_1)^{-1}$ and $\rho_3 = \rho_1 + (c_2/c_1)\rho_2 + (c_3/c_1)\rho_3$ (Fulle 2017). Porous ices and crystalline silicates provide $h/s = 0.9$ and $c_3\rho_3 = 1944$ kg m$^{-3}$, which imply an ice surface layer on Pluto with a thickness of $c_3 R/3 = 30$ km only, where $R$ is Pluto’s radius. Compact ices and amorphous silicates provide $h/s = 1.2$ and $c_3\rho_3 = 1720$ kg m$^{-3}$, which would make the bulk density of Pluto and Charon too inconsistent with a solar composition. The 67P $h/s$ ratios match the value measured in 1P/Halley (Jessberger et al. 1989) and are much larger than $h/s = 0.2$ assumed so far in models of Pluto and Charon (McKinnon et al. 1997). Impacts, tidal stress and the decay of radionuclides may decrease the pristine ice content during KBO lifetimes, implying that the pristine KBO bulk density may increase in time, without in any way overcoming the upper limit $c_3\rho_3$.

5 CONCLUSIONS

For the first time, Rosetta data allowed us to constrain the dust-to-ices mass ratio in a Jupiter Family Comet by means of independent techniques. Also, thick dust deposits ubiquitous on 67P northern terrains allow us to infer that probably in all comets the dust-to-ices mass ratio inside the nucleus is twice that most often measured in the lost material, e.g. by the RSI experiment and by trail observations. The water mass fraction of the dust deposits is $\approx 5$ per cent, very close to the water mass fraction sublimating from the average nucleus surface, thus making similar the activity from pristine terrains and that coming from the deposits. We obtain a pristine ice volume fraction of the 67P nucleus close to 20 per cent, matching that directly provided by the bulk density of Pluto, Charon and Triton, just assuming that the composition of their non-volatile material is that measured in comets (Fulle 2017). The possible highly variable content in carbon and the ice volume fraction in comets and KBOs, lower than in CI-chondrites, suggest multiple scenarios of their formation. Ice objects in the protoplanetary disc may have formed everywhere outside the water snowline, with a composition of non-volatiles apparently independent of the solar distance during accretion, thus confirming a fast mixing of non-volatiles in the protoplanetary disc (Ciesla 2011). This is further confirmed by the sub-mm aggregates of minerals of bulk density $>4000$ kg m$^{-3}$ observed by GIADA in 67P (Fig. 1). These minerals can have been formed only in the inner solar protoplanetary disc (Brownlee 2014). The variable ice content in KBOs suggests important migrations of the most icy objects (possibly comets and KBOs with a CI-chondritic composition of non-volatiles) outside the water snowline, where they may have accreted. Memory of the accretion sun-distance may be preserved by the ratios D/H, O$_2$/H$_2$O and N$_2$/H$_2$O (Fulle et al. 2016b).

ACKNOWLEDGEMENTS

Rosetta is an ESA mission with contributions from its member states and NASA. Rosetta’s Philae lander is provided by a consortium led by DLR, MPS, CNES and ASI. We thank all the Rosetta instrument teams, the Rosetta Science Ground Segment at ESAC, the Rosetta Mission Operations Centre at ESOC and the Rosetta Project at ESTEC for their outstanding work enabling the science return of the Rosetta Mission. GIADA was built by a consortium led by the Univ. Napoli Parthenope & INAF – Oss. Astr. Capodimonte, in collaboration with the Inst. de Astrofisica de Andalucia, ES, Selex-FI-IT and SENER-ES. GIADA is presently managed and operated by Ist. di Astrofisica e Planetologia Spaziali-INAF, IT. GIADA was funded and managed by the Agenzia Spaziale Italiana, IT, with the support of the Spanish Ministry of Education and Science MEC, ES. GIADA was developed from a PI proposal from the University of Kent; science and technology contribution were provided by CISAS, IT, Lab. d’Astr. Spat., FR, and Institutions from UK, IT, FR, DE and USA. Science support was provided by NASA through the US Rosetta Project managed by the Jet Propulsion Laboratory/California Institute of Technology. We would like to thank Angela Coradini for her contribution as a GIADA Co-I. GIADA calibrated data will be available through ESA’s PSA website (http://www.rssd.esa.int/index.php?project=PSA&page=index). All data presented here are available on request prior to its archiving in the PSA. This research was supported by the Italian Space Agency (ASI) within the INAF-ASI agreements I/032/05/0 and I/024/12/0. SFG acknowledges the financial support of UK STFC (grant ST/L000776/1).

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