Published in final edited form as:
Space Sci Rev. 2018 ; 214: . doi:10.1007/s11214-018-0496-3.

Cometary Dust

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Abstract

This review presents our understanding of cometary dust at the end of 2017. For decades, insight about the dust ejected by nuclei of comets had stemmed from remote observations from Earth or Earth's orbit, and from flybys, including the samples of dust returned to Earth for laboratory studies by the Stardust return capsule. The long-duration Rosetta mission has recently provided a huge and unique amount of data, obtained using numerous instruments, including innovative dust instruments, over a wide range of distances from the Sun and from the nucleus. The diverse approaches available to study dust in comets, together with the related theoretical and experimental studies, provide evidence of the composition and physical properties of dust particles, e.g., the presence of a large fraction of carbon in macromolecules, and of aggregates on a wide range of scales. The results have opened vivid discussions on the variety of dust-release processes and on the diversity of dust properties in comets, as well as on the formation of cometary dust, and on its presence in the near-Earth interplanetary medium. These discussions stress the significance of future explorations as a way to decipher the formation and evolution of our Solar System.

Keywords

Dust; Comets; Jupiter-family comets; Organics; Aggregates; Rosetta; Stardust; Comets: coma, nucleus, trail; Comets: individual: 1P/Halley, 9P/Tempel 1, 67P/Churyumov-Gerasimenko, 81P/Wild 2, C/1995 O1 Hale-Bopp; Solar System formation; Comet formation; Origin of life; Cosmic dust; Solar nebula

1 Introduction

By the middle of the XXth century, [Whipple 1950] inferred, through his analysis of the non-keplerian motion of comets, the existence of cometary nuclei consisting of ices embedded with dust, i.e. micron-sized non-volatile particles. Dust ejected with gases from the nuclei, in combination with solar gravity and radiation pressure when comets approach the Sun, was recognized as the means by which the long-yellowish cometary dust tails are produced (e.g., [Brandt and Chapman 1981]). Significant progress in our understanding of cometary dust has been achieved, since the 1980's, by a series of space missions performing flyby of nuclei and by remote observations of dust in cometary environments, as summarized below.

1.1 Past Flyby Missions to Comets

The choice made in 1980 by the European Space Agency (ESA), to perform a flyby of comet 1P/Halley soon after its perihelion passage, triggered in situ space exploration of cometary dust. The soviet Vega missions complemented the European Giotto mission, allowing, through the pathfinder concept, to flyby the nucleus with a miss-distance of about 600 km in March 1986. Vega also provided unique results on dust elemental composition within 1P/Halley's coma; the PUMA instrument (Dust Impact Mass Analyser) on board Vega-1 discovered dust particles to consist of rock-forming minerals, and also of carbon-hydrogen-oxygen-nitrogen compounds, so-called CHONs [Kissel et al. 1986a] [Krueger et al. 1991].

On board Giotto, DID (Dust Impact Detector) and OPE (Optical Probe Experiment) monitored dust impacts and dust scattering properties along the trajectory of the spacecraft within the coma. OPE, through measurements of the solar light locally scattered by dust, determined changes in the dust properties [Levasseur-Regourd et al. 1999]. In addition, a comparison between DID and OPE dust data suggested, through a non-isotropic dust dynamical model, the geometric albedo and the density of the dust particles to be extremely low, ranging between 3% and 10% and between 50 and 500 kg m^{-3}, respectively [Fulle et al. 2000]. No significant distributed gas sources were identified, implying no significant sublimation of dust [Rubin et al. 2011]. After its successful mission to 1P/Halley, Giotto in 1992 flew-by a Jupiter Family Comet (JFC), 26P/Grigg-Skjellerup. The presence of a possible fragment of the nucleus was suspected within its coma [Levasseur-Regourd et al. 1993]. Although the data were consistent with impacts of large particles on the spacecraft generating a transient dust cloud [Le Duin et al. 1996], the presence of a fragment of the main nucleus was also inferred from fluctuations in the energetic particle data recorded by EPONA experiment on board Giotto [McKenna and Afonin 1999].

In subsequent years four more JFC comets were visited by NASA spacecraft, from Deep-Space 1 at 19P/Borrelly in 2001 to Stardust-NExT at 9P/Tempel 1 in 2011. The densities of the nuclei of 9P/Tempel 1 and of 103P/Hartley 2, previously estimated from non-gravitational forces effects, were confirmed to be significantly smaller than 10^3 kg m^{-3}, implying that they are very porous objects (e.g., [Barucci et al. 2011]). Stardust mission to 81P/Wild 2 in 2004 confirmed the presence of organic compounds [Brownlee et al. 2004]. Clusters of dust within 81P/Wild 2 and 9P/Tempel 1 comae were interpreted in terms of dust fragmentation [Tuzzolino et al. 2004] [Economou et al. 2013]. The Deep Space 1 mission to comet 19P/Borrelly in 2001 granted further evidence of spatially complex coma dust distributions.

In addition, samples of cometary dust collected in the Stardust return capsule provided exceptional results on cometary dust collected during the 6.1 km s^{-1} flyby in the coma of 81P/Wild 2. Analyses of dust impacts on aluminum foils or tracks within aerogel cells established the presence of particles of different internal tensile strength [Brownlee et al. 2006] [Hörz et al. 2006] [Burchell et al. 2008] and of complex organics (most likely including glycine) with heterogeneous and unequilibrated distributions [Matrajt et al. 2008] [Elsila et al. 2009].

To summarize, studies during cometary flybys of dust particles ejected by the dark and highly non-spherical nuclei of comet 1P/Halley and of five JFCs, suggest that cometary dust is not only rich in organic compounds, but also diverse, dark, and quite porous (see e.g. for review [Kolokolova et al. 2004] [Cochran et al. 2015]).

1.2 Past Remote Observations of Dust in Comae, Tails and Trails

Remote observations of cometary dust have been mostly triggered by space missions to comets, by the passage of new spectacular comets, such as C/1995 O1 Hale-Bopp, by new observational techniques, such as infrared surveys, and by the development of various numerical models and experimental simulations.

The spectroscopic observations of Hale-Bopp in the near infrared from the ISO space telescope showed that particles emitted from the nucleus contained silicates, particularly magnesium-rich crystalline olivine (forsterite) and crystalline magnesium-rich pyroxenes, along with a large proportion of amorphous silicates [Crovisier 1997] [Wooden et al. 1999]. The detection in spectra of crystalline material provided a first hint that some minerals in cometary dust had encountered high temperatures during their history before being stored in the comet nucleus, implying that they are not only consisting of amorphous grains directly inherited from the presolar cloud (see e.g. for reviews [Cochran et al. 2015] [Wooden et al. 2017]).

The brightness and partial linear polarization (thereafter referred to as polarization) of solar light scattered by dust in the comae of bright comets (including the spectacular C/1995 O1 Hale-Bopp) and of targets of space missions have long been monitored from Earth-based observatories. Of major interest are brightness images, which have made it possible to point out anisotropies in dust density within comae, and to infer from them constraints on the spin axis orientation of various comets, and the variations of a given set of observations with the phase angle (α), possibly accessible from the backscattering region near 0 deg to about 100 deg, and the wavelength (λ).

The main interest of the polarization is that, except very close to the nucleus, it does not vary with the dust spatial density, nor with the distances to the Sun and to the observer. It just varies with α and λ, and it depends on the bulk properties of dust along the line of sight, such as the size, the structure and the complex refractive indices, and thus the geometric albedo [Levasseur-Regourd and Hadamcik 2003] [Kolokolova et al. 2004]. The first combination of polarimetric measurements obtained by various teams on Earth and from a space probe took place during 1P/Halley return in 1985-1986 [Dollfus et al. 1988]; OPE on Giotto provided clues [Levasseur-Regourd et al. 1999] to changes in dust properties from measurements in three visible spectral domains at α = 73 deg and from about 10^3 to 10^5 km from the nucleus.

Local and remote measurements of the polarization of cometary dust are most delicate, since they need to be performed through narrow interference filters. Such filters, which were already developed for 1P/Halley observations (typically through the international Halley Watch) to avoid the contamination by less-polarized molecular bands, reduce the intensity of the collected light [Levasseur-Regourd 1999] [Kiselev et al. 2004]. Developments in remote imaging polarimetry made it possible to distinguish between anisotropies in dust density and changes in intrinsic dust properties, and have confirmed the existence of such changes within jetlike coma features and inner comae, below a few thousands of km from the nucleus [Renard et al. 1996] [Hadamcik et al. 1996]. Data on whole coma polarization have been used to build up polarimetric phase curves for comets extensively observed by various teams, at different times and thus different phase angles. Within a given wavelength range, free of gaseous emissions, phase curves are well defined; their smoothness may be indicative of scattering by irregular particles [Levasseur-Regourd et al. 1996] [Kiselev et al. 2015]. For $\alpha \geq 25$ deg, the polarization usually increases with increasing wavelength, at least up to 2 μm, where infrared emission is still negligible. Different types of dust properties have been suggested, from the positive branches (at least from $\alpha \geq 25$ deg) of the phase curves within a given wavelength range, with high-polarization comets that usually also present a strong silicate emission feature near 10 μm [Levasseur-Regourd 1999].

Outbursts in activity of cometary nuclei (seldom observed remotely), as well as partial fragmentation and total disintegration of nuclei, and even induced impacts (from Deep Impact mission), have been noticed to lead often to an increase in polarization within the coma [Hadamcik and Levasseur-Regourd 2003] [Furusho et al. 2007]. It may be speculated that such events triggered the ejection of dust particles stored deep enough inside the nucleus to present slightly different dust properties. Cometary polarization curves are generally consistent with light scattering by a population mixing irregular dust particles with more compact large particles, and with optical indices similar to silicates and absorbing organics [Lasue et al. 2009] [Kolokolova and Kimura 2010], as detailed and compared with recent in situ results in Subsec. 5.2.

Dust is accelerated in the coma by the gas pressure up to a terminal velocity which also depends on the dust size. Dust with such an ejection velocity leaves the coma, and is swept into the dust tail by the solar radiation pressure. Monte-Carlo models of dust tails have provided information on the time evolution of the dust loss rate, size distribution and ejection velocity for many long and short period comets [Fulle 2004], showing that the dust mass, and sometimes also the optical cross-section, is dominated by the largest ejected chunks.

Finally, many short-period comets are followed in their orbital motion by a trail of debris with sizes typically above 100 μm and up to meters. Due to their low cross-section-to-mass ratio, such dust particles are only little affected by solar radiation pressure and remain close to the parent body’s orbit for many revolutions around the Sun, before they are eventually dispersed by planetary encounters [Soja et al. 2015]. Infrared observations from space led to the discovery of debris trails as narrow and elongated structures along the orbits of periodic comets [Davies et al. 1984] [Sykes et al. 1986] [Reach et al. 2007]. Trails represent an intermediate step between the cometary dust and the meteoritic streams [Kresak 1993] [Koschny et al. this issue].

Following their discovery with the Infra Red Astronomical Satellite (IRAS) [Sykes et al. 1986], [Sykes et al. 1992], surveys at thermal infrared and visible wavelengths have been conducted [Reach et al. 2007] [Ishiguro et al. 2009], and trails of some individual comets have been the subject of targeted observations. The width of a trail and its surface brightness as a function of the nucleus distance have been used to constrain the dust ejection velocities, past production rates and size distribution through numerical modelling of the dust motion under the influence of solar gravity and radiation pressure [Reach et al. 2000] [Ishiguro et al. 2003] [Saragaku et al. 2007] [Ishiguro et al. 2008] [Kelley et al. 2008] [Stevenson et al. 2014]. Ejection velocities are of the order of m s^{-1} [Sykes et al. 1990] [Davies et al. 1997].

The combination of observations in scattered visible and thermal infrared light yields a dark geometric albedo of a few percent [Ishiguro et al. 2002] [Agarwal et al. 2010] [Saragaku et al. 2015]. Trails are associated with a large fraction of the observed short-period comets and can be considered one of their generic features [Reach et al. 2007]. The derived production rates of trail material suggest that cm-sized particles dominate the optical cross-section of dust released from comets [Reach et al. 2007] [Agarwal et al. 2010] [Vaubaillon and Reach 2010] [Arendt 2014]. Dust production rates derived from trail formation models are therefore a good proxy for the total loss rate of refractory material from a comet [Reach et al. 2000].

The next section presents the context of the Rosetta rendezvous mission, which has recently allowed significant progress in our understanding of cometary dust. Key results on the composition and on the physical properties of dust particles are then developed in sections 3 and 4, with emphasis on Stardust samples and on Rosetta in situ analyses. Finally, various topics related to cometary dust release to comparisons with other approaches, and to implications for topics related to origins are discussed in Sec. 5.

2 Context of the Rosetta Mission

One of the main objectives of the mission was to characterize the properties of the dust released by the nucleus of a Jupiter Family Comet, together with its evolution through a long-duration rendezvous [Glassmeier et al. 2007]. The Rosetta cometary probe accompanied 67P/Churyumov-Gerasimenko comet (thereafter 67P/C-G) from August 2014 to September 2016. During its 26-month investigation, the solar distance decreased from about 3.6 au (astronomical units) down to 1.2 au at perihelion (13 Aug. 2015), and then increased again up to 3.8 au. Meanwhile, the distance of Rosetta to the nucleus decreased to about 10 km before the release of the Philae lander (12 Nov. 2014) and to a few meters, when the signal was cut off immediately before the landing of Rosetta (30 Sept. 2016), while increasing by several hundred kilometres whenever the comet was very active.

2.1 Rosetta Dust Instruments

Among the 11 instruments on board Rosetta, 3 were specifically dedicated to the study of cometary dust (Fig. 1). COSIMA (Cometary Secondary Ion Mass Analyser) collected dust particles, imaged them with the CosiScope optical microscope with a resolution of 14 μm per pixel, and analysed their composition with a mass spectrometer. GIADA (Grain Impact Analyser and Dust Accumulator) measured the optical cross-section, speed and momentum for particle sizes of about 0.1 to 1 mm, and the cumulative flux of dust particles smaller than 5 μm. MIDAS (Micro-Imaging Dust Analysis System), an atomic force microscope, imaged the 3D surface in the tens of nanometers to micrometres size range. Other instruments could detect dust additionally to their main science goals. For instance, the scientific camera system on board, OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System) detected dust and debris over a wide range of sizes and distances from the spacecraft, which allowed the dust phase function to be retrieved, while the bistatic radar on board Rosetta and Philae, CONSERT (Comet Nucleus Sounding Experiment by Radiowave Transmission), provided information about the porosity and the sizes of the voids within the small lobe of the nucleus.

The COSIMA instrument collected, imaged and finally analysed the dust with a time of flight secondary ion mass spectrometer (TOF-SIMS) [Kissel et al. 2007]. Dust collection was achieved by exposing three 1 cm^2 targets to the cometary dust stream for durations of hours to days. Afterwards, a robotic unit brought the targets to one of the analytical stations. The first step was to image the targets using the CosiScope with a resolution of 14 μm pixel^{-1}. Selected particles were then probed by TOF-SIMS: The surface layers of the dust were irradiated with a pulsed indium ion beam (of $35 \times 50\ \mu\mathrm{m}^2$) to generate secondary ions representative of the composition of the sampled area. The masses and numbers of either the negative or the positive ions were then determined, allowing the identification of the relative composition of the surface of the dust particles. With a mass resolution ($m/\Delta m$) of about 1400 (full-width half maximum of 100) the separation of elements from organic ions containing hydrogen from the same integer mass is in most cases possible. COSIMA also carried a chemical station to warm the targets prior to exposure to either clean them or study the evolution of samples. To summarize, COSIMA determines the elemental and isotopic composition, sheds light on the molecular composition, and characterizes the morphology for particles between 14 μm and a few hundred μm.

The GIADA instrument determined the physical properties of the dust in real time, including momentum, speed and cross-section of the individual particles [Colangeli et al. 2007] [Della Corte et al. 2014]. These parameters enabled the determination of the dust flux and of the mass of the individual particles, the estimation of the shape and density of the particles, and the place of origin of the dust on the nucleus. GIADA had three subsystems: Grain Detection System (GDS), Impact Sensor (IS) and Micro-Balances System (MBS). GDS consisted of a 3 mm thin light curtain created with 4 laser diodes; if a particle passed the curtain it scattered the light, which was then detected by 4 photodiodes; calibration indicates that the sizes range from about 0.1 to 1 mm [Ferrari et al. 2014]. The IS is a 0.5 mm thick and ($0.1 \times 0.1\ \mathrm{m}^2$) sized aluminium diaphragm equipped with 5 piezoelectric sensors; if a particle impacted the IS, the momentum and the time difference between GDS and IS signal were measured. Finally, the MBS consisted of 5 quartz microbalances sampling all the 2π solid angle of space outside the Rosetta payload and dedicated to the measurement of the cumulative flux of particles below 5 μm in size.

The MIDAS instrument was the first atomic force microscope (AFM) to be flown in space [Riedler et al. 2007]. It collected dust particles and imaged their surfaces in 3D with resolutions of a few nanometres to a few μm. MIDAS had 64 targets of about 3.5 mm^2 cross-section, mounted on a wheel. For particle collection the wheel could drive a target to the position behind a focussing funnel with a shutter that could be opened for dust exposure. To image the collected dust, the target was moved to the AFM part of the instrument. It consisted of 16 tips on a piezoelectric XYZ-stage that allowed accurate movement across the target. The height measurement was performed by amplitude-modulated atomic force microscopy. A typical scientific sequence of MIDAS was to pre-scan an area of a target, expose it to the dust flux of the comet, and re-scan the same area with low resolution.

Possibly detected dust particles were then scanned with optimised parameters. The results are three dimensional surface images of cometary dust that allow the determination of size, shape and morphology.

OSIRIS was the scientific camera system on board Rosetta, consisting of a Narrow Angle Camera (NAC) and a Wide Angle Camera (WAC) [Keller et al. 2007]. During the Rosetta mission, both cameras regularly observed the nucleus and the coma in different filter bands, monitoring the surface and the gas and dust environment of the comet. In addition to the diffuse background of unresolved dust, OSIRIS regularly provided images of individual dust particles. Depending on the circumstances, it was possible to constrain the sizes of the dust particles, their velocities, rotation rates, and/or colour and to retrieve the dust phase function.

VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) obtained information on the composition and physical properties of dust both on the surface of the nucleus and in the coma [Coradini et al. 2007].

Finally, CONSERT (Comet Nucleus Sounding Experiment by Radiowave Transmission) was a bistatic radar, designed to provide unique information about the interior of the nucleus, by propagating electromagnetic waves (at 90 MHz, i.e. by 3 m wavelength) between the Philae lander and the Rosetta probe [Kofman et al. 2007]. The CONSERT radar probed the small lobe of 67P/C-G to depths of a couple of hundred meters, providing constraints on its internal structure [Ciarletti et al. 2017].

2.2 Remote Observations of Dust in 67P/C-G

Once 67P/Churyumov-Gerasimenko was chosen as the target of the Rosetta rendezvous mission, numerous remote observations were performed during the 2008-2009 return and carefully analyzed in preparation of the Rosetta mission. Polarimetric observations provided clues to a seasonal effect, as well as to the presence of both rather large particles and small grains, likely in the form of fluffy aggregates [Hadamcik et al. 2010] [Hadamcik et al. 2016]. Dust coma structures have constrained properties of the dust and of the nucleus of 67P/C-G [Vincent et al. 2013], although the links between the coma structures observed at large scale [Snodgrass et al. 2017] and those detected by Rosetta still need to be clarified. Tail modelling of 67P/C-G has provided information useful to plan the Rosetta mission, such as the expected dust flux and the contamination to star-trackers frames by individual dust particles [Fulle et al. 2010]. The dust size distribution showed a strong time-evolution, with the optical cross-section dominated by the largest ejected dust before perihelion, and by the smallest ejected dust after [Fulle et al. 2004] [Moreno et al. 2010] [Fulle et al. 2010].

The debris trail of comet 67P/C-G was observed multiple times prior to the Rosetta mission. It was discovered by IRAS [Sykes et al. 1992], and subsequently observed in both visible and thermal infrared light [Ishiguro et al. 2008] [Kelley et al. 2008] [Agarwal et al. 2010]. Numerical models aiming to reproduce the observed surface brightness find that the production rate of about 0.1 mm-sized particles around perihelion must have been sufficiently high to also dominate the surface brightness of the coma at that time, without a strong additional contribution by smaller particles that would not subsequently populate the debris trail; sizes are in the 0.1 to 100 mm range, with an albedo of a few percent [Agarwal et al. 2010] [Soja et al. 2015].

A unique long-term campaign [Snodgrass et al. 2016a] [Snodgrass et al. 2016b] [Snodgrass et al. 2017] of remote coordinated observations of 67P/C-G, from ultraviolet to radio wavelengths, was organized for the 2013-2016 return, in order to contribute to the support the mission through early characterization of the comet [Snodgrass et al. 2016a] and to provide numerous remote observations, including observation of dust in 67P/C-G coma, tail and trail [Snodgrass et al. 2016b] [Moreno et al. 2016] [Moreno et al. 2017]. Although the observing conditions from Earth or its environment were difficult due to the comet's low surface brightness and its low solar elongation around its perihelion passage, numerous observations took place, from a wide range of telescopes distributed on a broad geographical spread, including robotic instruments [Snodgrass et al. 2016b], large ground based telescopes, such as the Russian 6-m [Rosenbush et al. 2017] and space telescopes, such as HST [Hadamcik et al. 2016]. The level of activity and the peak in activity dust brightness (about 2 weeks after perihelion passage) were consistent with 67P/C-G observations at previous returns; an extensive review of all these observations is provided in [Snodgrass et al. 2017].

Such remote observations should provide a link between the ground-truth provided by Rosetta, to be presented in the next two sections, and future remote observations of other JFCs, including observations of cometary dust.

3 Composition of dust particles

Deciphering the composition of cometary dust particles is a key to understanding where and when they formed, and what were the physico-chemical conditions of their formation environment. Composition can be addressed from four main points of views: the elemental composition, the mineralogy of the dust particles, their organic content and the isotopic fractionation of some of their elements. Being building blocks of cometary nuclei, these dust particles provide valuable information about comets, which may be more easily accessible than direct measurements of the nucleus and its interior.

3.1 Elemental composition

The relative abundance of chemical elements in an object of the Solar System is a useful tool to assess the degree of "pristinity" of the object, i.e. the extent to which it was submitted to transformation (mainly differentiation) since its formation 4.5 Ga ago. The closer to the solar photosphere composition, the more the object has kept a composition close to the one of the solar nebula where it accreted. Carbonaceous chondrites of the CI type (such as the Orgueil meteorite) are the most chemically primitive meteorites, their elemental composition being very similar to that of the solar photosphere. CI carbonaceous chondrites are commonly used as a reference for comparison with other objects in the Solar System. Most of their elements have a "solar abundance" to within 10% [Lodders 2010]. Light elements H, C, O, N and noble gases are exceptions. If these elements display a rather low abundance in CI meteorites relative to the solar photosphere, they may have not been accreted in the parent body of the meteorite since they were not present in the solid phase at that time and parent bodies of the chondrites formed in the warm inner Solar System. Comets, however, are expected to have formed in the outer Solar System, at low temperature, hence they are expected to contain more light elements than CI chondrites.

As briefly mentioned in Subsec. 1.1, the elemental composition of some of the main constituents have been measured in dust particles emitted from comets 1P/Halley, 81P/Wild 2 and 67P/C-G. The two spacecraft flying by lP/Halley in March 1986 (Vega 1 and Giotto) revealed that the dust particles were a mixture of mineral and organic matter [Lawler and Brownlee 1992]. A mean elemental composition was measured in the particles that impacted the mass spectrometers at very high velocities (about 77 km s^{-1} for Vega 1 and 2, and 68 km s^{-1} for Giotto). Results showed that comet 1P/Halley dust particles have a chondritic composition within a factor of two for most of the elements detected. However, they are enriched in three elements: carbon (×11), nitrogen (×8) and hydrogen (×4). The conclusion was that comets would be therefore less altered and more primitive than carbonaceous chondrites CI [Jessberger et al. 1988].

The Stardust mass spectrometer [Kissel et al. 2004] revealed the importance of organic matter in 81P/Wild 2 coma. The results on light elements were inconclusive during the flyby and could not be confirmed in samples returned by Stardust from 81P/Wild 2 [Brownlee et al. 2006] [Hörz et al. 2006]. Because the materials were captured at 6.1 km s^{-1} in aerogel and aluminum foil collectors, organics and other fragile materials were severely affected [Brownlee 2014] [Keller et al. 2006] [Sandford et al. 2010]. Elements such as C and N could not be measured, and volatile elements such as S were apparently vaporized and redistributed as a halo around the tracks in aerogel [Ishii et al. 2008a] or were lost from residues in craters in the Al foil. The other elements that could be quantified displayed chondritic abundance [Flynn et al. 2006] [Ishii et al. 2008b] [Lanzirotti et al. 2008] [Leroux et al. 2008] [Stephan et al. 2008] but with large error bars because of the strong heterogeneity among particles. Much more about the mineralogy of cometary particles was learned from Stardust and will be discussed in the next subsection.

The composition of dust particles emitted from the Jupiter family comet 67P/C-G was measured with the COSIMA instrument on board the Rosetta spacecraft. Analyses with COSIMA differ from those of previous missions in two aspects: (1) the Rosetta spacecraft followed the nucleus for about 26 months through a large portion of its orbit, as opposed to previous flyby spacecraft that spent only a few hours within the coma; COSIMA collected more than 35,000 cometary particles and fragments [Merouane et al. 2017], with sizes ranging from about 10 to 1000 μm, and about 250 of them could be analysed; (2) The low impact velocity of the collected particles, < 10 m s^{-1} [Rotundi et al. 2015], on the COSIMA targets preserved the dust chemical properties and part of the physical structure (e.g. the porosity of the particles) [Hornung et al. 2016] [Langevin et al. 2016].

The relative elemental composition of 67P/C-G particles have been measured in about 30 particles for the following elements: C, N, O, Na, Mg, Al, Si, K, Ca, Cr, Mn and Fe [Bardyn et al. 2017] [Fray et al. 2017]. As shown in Fig. 2, relative abundances in 67P/C-G are roughly chondritic, except for C and N. This is broadly similar to the results from 1P/Halley and 81P/Wild 2. In 67P/C-G, $C/Si = 5.5^{+1.4}_{-1.2}$, which is close to the protosolar abundance of

7.19±0.83 (to be compared to 0.76 ± 0.10 found in CI carbonaceous chondritic meteorites) [Lodders 2010]. Regarding N abundance (N/C = 0.035±0.011 [Fray et al. 2017]), which is strongly depleted compared to protosolar value of N/C = 0.3±0.1 [Lodders 2010] and quite similar to values found in CI chondrites (N/C = 0.04 [Alexander et al. 2012]). Some caution has to be taken in comparing data in representations such as Figure 2, which shows a double normalization: to Fe and then CI abundances. No absolute value could be measured, only elemental ratios. For instance, in comet 67P/C-G particles, C/Si ratio is calculated in the particles on the basis of a standard material with a known composition (silicon carbide) measured with the ground COSIMA instrument. For some other elements, for instance Si, this is Si/Fe, which is measured (on the basis of a San Carlos olivine standard). Hence, for the purpose of comparison, every elemental ratio has to be normalized to the same element, here Fe was chosen (from which other normalizations such as C/Si and N/C follow, which increases error bars in Fig. 2). Those ratios are subsequently normalized to the same ratio measured in CI chondrites. The selection of Fe for normalization leads to the conclusion that, for instance, Si appears to be in excess in both comets 1P/Halley and 67P/C-G. If normalization would have been performed relative to Si, then Fe would appear to be depleted. Nonetheless, the abundance of Si and Na show a similar trend in comets 1P/Halley and 67P/C-G. Na was also observed in the upper atmosphere of Mars by the MAVEN spacecraft, as the most abundant element detected during the ablation of particles from the passage of comet C/2013 A1 [Benna et al. 2015]. Mg and Ca are quite low in 67P/C-G, which is not understood. The high K in Fig. 2 is based on TOF-SIMS analyses of craters in the Al foil of Stardust and of slices of tracks in the aerogel [Stephan et al. 2008]. K was detected in only 2 craters out of 7 analysed, and in 5 tracks out of 21 analysed, thus providing only an estimate but not a bulk value [Flynn et al. 2006].

One important feature of 67P/C-G data is that the particles have been collected throughout the 26 months of the mission, at various heliocentric distances and most probably from different locations on the nucleus, and they show different morphologies. However, they display a quite similar composition, which might indicate a rather homogeneous composition of the dust in the nucleus. The data for the three comets points toward rather primitive bodies, globally close to solar abundance, except for nitrogen, which, although enriched with regard to the CI composition, is always strongly depleted with regard to the solar value.

3.2 Mineralogy

Mineralogy of the cometary dust particles has long been quite poorly constrained. However, several measurements are now available to get a better picture of the mineralogy of cometary dust. Historically, remote sensing observations in the infrared range have first been used to get a grip on the composition.

The Spitzer Space Telescope imaging spectrometer characterized the ejecta from comet 9P/Tempel 1 produced by the Deep Impact encounter [Lisse et al. 2006]. 5- to 35-micrometer emission spectra of the ejecta were obtained, allowing to identify specific minerals and infer their relative proportions. This emission is inhibited at dust grain sizes below the wavelength of the emission, so the technique is much less sensitive to sub-micron grains, and for larger grains the emission is proportional to the surface area of the grain, so surface area weighted abundances were reported rather than mass weighted abundances. Conversion to mass or molar fractions requires the assumption that all minerals have the same size-frequency distribution, but hypervelocity disruption experiments on different types of meteorites show different size-frequency distributions, suggesting the distribution may be different for different minerals [Flynn et al. 2005a]. In addition, the best fit to the spectral data depends on the basis set of minerals selected for inclusion in the fitting routine. With these limitations, the spectrum was best fit by 18.2% of the emission from forsterite, 10% from amorphous silicate, 18.8% from Mg-Fe-sulfide, 8.2% from clay, 6.8% from diopside, 5.9% from orthoenstatite, 5.0% from fayalite, 4.7% from carbonates, 4.0% from amorphous carbon, 2.3% from ionized PAHs, and only 2.9% from water ice crystals, with the remainder from gaseous water and minor phases [Lisse et al. 2006]. No assessment was done of the possibility of either mineral destruction or formation from the shock and heating of the high speed impact which deposited about 2×10^{10} J of kinetic energy into a localized region on 9P/Tempel 1.

Samples returned by the Stardust mission contain thousands of particles from less than 1 μm to about 100 μm [Brownlee 2014]. They enabled a detailed analysis of the mineralogy of cometary dust particles returned from comet 81P/Wild 2. Relatively refractory materials - silicates, oxides, sulfides and metals - were captured in the aerogel collectors with little alteration, and, over the decade since recovery, have been the subject of intense scrutiny in terrestrial laboratories. Key observations from the analysis of about 5% of the total collection studied so far include:

1. Although interstellar silicates are known from astronomical observations to be almost entirely amorphous, approximately half of the silicates in 81P/Wild 2 samples are crystalline [Westphal et al. 2009] [Stodolna et al. 2014].
2. Among crystalline minerals, olivines, pyroxenes and Fe sulfides are the most abundant minerals present in the 81P/Wild 2 samples.
3. Approximately 1% of the particles recovered from 81P/Wild 2 are assemblages of highly refractory minerals, reminiscent of Calcium-Aluminum-rich Inclusions (CAIs) found in chondritic meteorites, which are thought to be high-temperature condensates and perhaps the first solids to have formed in the cooling inner solar nebula [Brownlee et al. 2006] [Zolensky et al. 2006] [Joswiak et al. 2017].
4. The collection also contains numerous small igneous “rocks” assemblages of minerals that apparently cooled from a melt. These are reminiscent of chondrules, found in chondritic meteorites, which are thought to be cooled melt droplets. The origin of chondrules is unclear (and is controversial), but it is certain that they do not share a common origin with CAIs, and generally appear to be a few Myrs younger than CAIs, based on ^{26}Al dating, although ^{26}Al ages are controversial [Ogliore et al. 2015] [Nakamura et al. 2008] [Kööp et al. 2016] [Gainsforth et al. 2015].
5. 81P/Wild 2 samples contained large amount of fine-grained matrix (individual size of minerals < 1 μm) that did not survive well the impact. This fine-grained

component got mixed with melted aerogel in the walls of the impact tracks and contains olivine, pyroxenes and Fe sulfides. The composition of this fine-grained component is close to the chondritic CI composition [Leroux et al. 2008] [Leroux 2012] [Leroux and Jacob 2013].

6. Although not common, Fe-Ni metal particles at least up to 20 μm in size are present in 81P/Wild 2. One particle that was studied in detail has an unusual composition reminiscent of metals found in ureilites, a family of meteorites that is poorly understood but may have a composition consistent with smelting of silicates in a carbon-rich environment, with Fe originally in silicates reduced to metal [Westphal et al. 2012] [Humayun et al. 2015].
7. Small amounts of minerals possibly resulting from aqueous alteration have been identified in 81P/Wild 2 samples, like magnetite grains [Stodolna et al. 2012], carbonates [Flynn 2008] [Flynn et al. 2009a] [Mikouchi et al. 2007] [Wirick et al. 2007] [Leroux 2012], and a copper iron sulfide (cubanite) in association with pyrrothite and pentlandite [Berger et al. 2011]. No hydrated silicates have been identified in 81P/Wild 2 samples.

These observations, combined with observations of oxidation state [Westphal et al. 2017] [Butterworth et al. 2017] [Keller and Berger 2014] are pointing to a dramatic and complicated process, perhaps including complete vaporization and recondensation of a substantial fraction of the material in the inner nebula, that must have been responsible for converting interstellar dust to nebular and cometary dust. Despite the evidence for the presence of inner Solar System material in 81P/Wild 2, the distribution of types and compositions of materials in 81P/Wild 2 differs from materials observed in meteorites.

1. The sizes of crystalline aggregates in Stardust samples are significantly smaller that those in meteorites (e.g. presence of micro-CAIS, micro-chondrules…).
2. Micro-CAIs found in 81P/Wild 2 do not span the entire range of volatility of CAIs observed in meteorites but are concentrated at the most volatile end of the CAI volatility distribution [Joswiak et al. 2017].
3. Microchondrules in 81P/Wild 2 are Fe-O rich, similar to type II chondrules, while chondrules in meteorites are dominated by those of type I (Fe-O poor) [Nakamura et al. 2008] [Gainsforth et al. 2015].
4. Olivines in 81P/Wild 2 are unequilibrated and show a wide range of Fe content, implying a wide sampling of materials from the protosolar disk [Frank et al. 2014].
5. Pyroxenes minerals are about as abundant as olivine in 81P/Wild 2, which is in sharp contrast with carbonaceous chondrites where the abundance of olivine mineral dominates over that of pyroxenes (except for CR chondrites).
6. Only a few presolar grains have been found in 81P/Wild 2, but it was shown that the collection procedure in the aerogel or on the aluminium foils potentially resulted in the destruction of a substantial amount of presolar grains [Floss et al. 2013] [Croat et al. 2015]. Once this collection effect is taken into account, the

corrected abundance of presolar grains in 81P/Wild 2 samples is on the order of 600-800 ppm, rather comparable to that of the most primitive Solar System material [McKeegan et al. 2006] [Stadermann et al. 2008] [Messenger et al. 2009] [Floss et al. 2013] [Leitner et al. 2010] [Leitner et al. 2012] [Floss and Haenecour 2016].

7. The oxidation state of Fe in 81P/Wild 2 is also not observed in any meteorite family, although the effects of thermal metamorphism and especially aqueous alteration in asteroids complicate this comparison [Westphal et al. 2009] [Leroux et al. 2009] [Ogliore et al. 2010] [Westphal et al. 2017].

In the case of the Rosetta mission at 67P/C-G, the mineralogy is not straight-forward to assess from the analyses of the dust instruments (COSIMA, GIADA and MIDAS). The analysis of reflectance spectroscopy measurements indicated the presence of opaque minerals at the surface of the comet, that could be Fe sulfides [Quirico et al. 2016]. The analysis of 67P/C-G by COSIMA, as well as the identification of size and density of the particles by GIADA are compatible with a composition including silicates, Fe sulfides and carbon [Bardyn et al. 2017] [Fulle et al. 2016b]. The ratio of amorphous to crystalline silicates could not be measured in situ. There is however no evidence from the COSIMA mass spectra analyzed so far for the presence of hydrated silicates in 67P/C-G dust particles [Bardyn et al. 2017] [Stenzel et al. 2017]. From these different characterisations, it appears that the mineralogy of cometary dust is highly diverse and shows sometimes unexpected components [Wooden et al. 2017].

There are clear differences between the inferred mineralogical content of the 9P/Tempel 1 ejecta from the Deep Impact mission, and the 81P/Wild 2 particles collected by Stardust despite both being focused in the 10 to 50 μm size range. The major difference is the detectable presence of hydrated silicates in 9P/Tempel 1 ejecta, but their absence in the 81P/Wild 2 material. This could be explained in 3 ways: i) the spectrum fit in 9P/Tempel 1 could be explained without the need for hydrated silicates, as those fits rely on mineral reference spectra that might not represent all spectral features related to shapes and minerals sizes in particular; ii) it could reflect the destruction of micrometer-sized hydrated silicates by hypervelocity aerogel capture in the 81P/Wild 2 samples, iii) it could be an indigenous characteristic of 81P/Wild 2. No evidence for hydrated silicate was found in the analysis of 67P/C-G dust particles so far [Bardyn et al. 2017]. Another clear difference is the olivine to pyroxene abundance ratio, which is about 2 to 1 in the 9P/Tempel 1 ejecta compared to about equal abundances in 81P/Wild 2 dust [Dobrica et al. 2009].

3.3 Organic Composition

Organic matter in comets can be divided into two components. The first is volatile, stored in an icy phase dominated by H_2O, CO_2 and CO, and is released from the nucleus into the cometary atmosphere when the comet gets close to the Sun on its elliptical orbit. Part of this volatile fraction is released directly from the nucleus when ices sublimate, while other compounds are ejected on dust particles that are ejected from the nucleus during the active phase of the comet and sublimate in the atmosphere. The second component is a refractory phase that remains solid either on the nucleus and on the particles.

Regarding the dust organic composition, though not operating as planned at the surface of the nucleus of 67P/C-G, two of the instruments of the Philae lander were able to detect a few new molecules from dust particles. During the first bounce of the lander above the surface of 67P/C-G, dust particles were lifted at first touchdown and serendipitously entered the instruments COSAC (Cometary Sampling and Composition experiment) and Ptolemy. Some volatile compounds were outgassed from the particles and were analysed by direct mass spectrometry. Detections of nitrogen bearing molecules, and for the first time, CH_3COCH_3 (acetone), CH_3CONH_2 (acetamide), C_2H_5CHO (propionaldehyde) and CH_3NCO (methyl isocyanate) were reported with the instrument COSAC [Goesmann et al. 2015], while a sequence of compounds that could be a signature of small chains of formaldehyde polymers were detected by the instrument Ptolemy [Wright et al. 2015]. Those results have recently been reconsidered and detection of CH_3NCO, CH_3CONH_2, C_2H_5CHO and formaldehyde polymers questioned in the light of other measurements performed by the ROSINA (Rosetta Orbiter Spectrometer for Ion and Neutral Analysis) instrument after an impact of dust particles in the instrument less than 10 minutes after their ejection from the nucleus, which means that some volatile compounds were not yet outgassed from the dust [Altwegg et al. 2017]. The mass spectra of all three instruments show very similar patterns of mainly CHO-bearing molecules that sublimate from particles at temperatures of 275 K. Detection of toluene (CeH_5CH_3) is also proposed. Glycine (NH_2-CH_2-CO_2H), the simplest of the amino acids, which are the building blocks of proteins, was also detected with ROSINA. Its distribution in the atmosphere of the comet 67P/C-G is consistent with a release from the dust particles heated in the cometary atmosphere, rather than a direct sublimation from the nucleus [Altwegg et al. 2016].

Since the exploration of comet 1P/Halley, it has been observed that a significant fraction of the cometary organic matter is also present in a phase remaining solid whatever the distance and temperature reached by the dust particles ejected from the nucleus [Fomenkova et al. 2004] [Kissel and Krueger 1987]. The nature of this refractory component has eluded a proper characterization for a very long time. Indeed, the measurements performed on the dust samples returned from comet 81P/Wild 2, regarding the organic matter, were hampered by the presence of a significant amount of carbon in the collecting aerogel, which made it rather difficult to unravel the actual cometary organic matter from the one already present in the aerogel, and a mixture of the two reacting together at the time of the impact of the particles in the aerogel [Sandford et al. 2010]. Nevertheless, the cometary organic matter detected can be split into three groups: one is similar to Insoluble Organic Matter (IOM) observed in carbonaceous meteorites, the second is highly aromatic refractory matter contained in nanoglobule-like features [De Gregorio et al. 2011], and the third a volatile aliphatic organic found as a halo [Sandford et al. 2006], similar to the S halo; detection of glycine originating from the dust particles was also reported [Elsila et al. 2009]. A quantification of the carbon content could not be achieved in Stardust samples, but it seems that 81P/Wild 2 particles are rather low in carbonaceous content compared to what was anticipated in comets. It was proposed that this low amount could be due to degradation during capture at high velocity, at about 6 km s^{-1} [Brownlee 2014]. It could however also be due to the sampling of an organic poor region of the coma, which is not representative of the whole comet [Westphal et al. 2017] [Zubko et al. 2012].

As discussed earlier, the elemental composition of dust particles captured in 67P/C-G coma at low velocity (about 10 ms^{-1}, possibly preserving the nature and structure of the particles) has been probed with the COSIMA instrument in the Rosetta spacecraft, throughout the 26 months of the mission. It has been shown that the carbon in dust particles is present in the form of macromolecules that bear mass spectral similarities with the Insoluble Organic Matter found in carbonaceous meteorites [Fray et al. 2016]. A recent quantification of this macromolecular component points to an abundance of roughly 45% in mass of the dust particles, regardless of the size, shape and period of collect of the particles [Bardyn et al. 2017]. It appears that in 67P/C-G particles, only this kind of complex macromolecular form could be detected at the spatial resolution of the instrument ($\approx 40\ \mu m$). This rather large amount of organic matter is consistent with values that were indirectly deduced from the density of the particles at (52 ± 8)% in volume of organic matter [Fulle et al. 2016b] and from the radar CONSERT permittivity characterization of the nucleus inferring a C/Si of at least 5.7 [Herique et al. 2016].

3.4 Isotopic Composition

Access to the isotopic composition of cometary dust particles requires direct measurements on the particles. Therefore they have only been extensively made on samples returned from comet 81P/Wild 2. At the time of writing, only very limited information has been derived from the Rosetta mission, but it is expected that more results will be published in the coming years.

Hydrogen, Carbon, Nitrogen, Sulfur isotopes—Measurements for H, C and N isotopes have only been made in Stardust samples so far, and in the organic phase. Unfortunately, 81P/Wild 2 samples are not very rich in organics, either due to the roughness of the hypervelocity capture that destroyed most of the organics, or because 81P/Wild 2 was not an organic-rich comet [Brownlee 2014]. The H, C or N isotopic composition of Stardust samples was reported [McKeegan et al. 2006] [Stadermann et al. 2008] [De Gregorio et al. 2011] [Matrajt et al. 2008] [Matrajt et al. 2013]. The D/H ratios vary between the terrestrial (V-SMOW) value and up to a factor of three that of V-SMOW. The ^{13}C / ^{12}C ratio shows moderate variations with regard to the terrestrial value ($\delta^{13}C$ from −20 to −50 per mil, here δ refers to relative differences). The ^{15}N / ^{14}N ratios cluster around the terrestrial value and are also consistent with values found in most meteorites, with the exception of a few analyses showing excesses in ^{15}N ($\delta^{15}N$ from +100 to +500 per mil). At the submicron level, ^{15}N-rich hotspots are found, with a maximum of 1300 ± 400 per mil in $\delta^{15}N$ are observed. Such elevated values are also found in IDPs and in some carbonaceous chondrites [Busemann et al. 2006] [Briani et al. 2009]. The sulfur isotopic composition of several 81P/Wild 2 impact residues and one sulfide captured in the aerogel was found compatible with solar isotopic composition [Heck et al. 2012] [Ogliore et al. 2012], showing that these S-rich components of 81P/Wild 2 were formed in the Solar System. A ^{33}S enrichment in a cosmic symplectite in Stardust samples was found, that could result from photochemical irradiation of solar nebular gas [Nguyen et al. 2015]. The sulfur isotopic composition of 67P/C-G dust is also compatible with the normal value [Paquette et al. 2017]. Unfortunately, only the ^{34}S and ^{32}S isotopes could be measured, so a potential ^{33}S excess could not be assessed for 67P/C-G dust.

***Oxygen* and Silicon *isotopes*—**The origin of the peculiar distribution of oxygen isotopic composition of Solar System materials has been controversial since the discovery of ^{16}O-rich materials [Clayton 1993] [Clayton et al. 1999]. In a three-isotope plot (^{17}O / ^{16}O vs. ^{18}O / ^{16}O), ^{16}O-rich phases, particularly CAIs, form a line with a slope close to 1. This line is unexpected in a system controlled only by mass-dependent fractionation effects, which gives a slope close to 1/2. Three leading models aim to explain the data falling on the slope 1 line: i) mixing between the initial ^{16}O-rich solar value [McKeegan et al. 2011] and an ^{16}O-depleted reservoir resulting from the self-shielding of the CO molecule [Lyons and Young 2005]; ii) mass-independent fractionation could explain the data without the need of mixing several reservoirs [Thiemens and Heidenreich 1983] [Thiemens 1999] [Chakraborty 2008], iii) and presolar heterogeneous chemistry and later mixing between two presolar reservoirs with different O isotopic compositions [Dominguez 2010]. Oxygen isotopes of cometary dust could only be measured with precision on the returned Stardust samples, using micro- and nanoanalytical techniques. The coarse-grained particles from 81P/Wild 2 exhibit O isotopic composition that is broadly consistent with that of chondritic meteorites and their components, with olivine and pyroxenes plotting in the carbonaceous chondrite range, while refractory minerals are ^{16}O-rich [McKeegan et al. 2006] [Nakamura et al. 2008] [Simon et al. 2008] [Bridges et al. 2012] [Nakashima et al. 2012] [Ogliore et al. 2015] [Defouilloy et al. 2017]. There are however differences, like the recent measurement of Mg-rich pyroxenes that are ^{16}O-rich, suggesting a condensation origin for these minerals [Defouilloy et al. 2017]. The statistics are not yet sufficient to distinguish between them, but the correlation of oxygen isotopic composition of olivine and pyroxene with iron content shows evidence for an affinity with silicates in CR meteorites and Tagish Lake-like chondrites [Defouilloy et al. 2017]. Some fine-grained materials in 81P/Wild 2, however, preserved in the bulbs of tracks in aerogel, show a much larger dispersion in oxygen isotopes, extending the CCAM line from the terrestrial value to very ^{16}O-poor materials [Ogliore et al. 2015], up to 200 per mil, similar to cosmic symplectite [Sakamoto et al. 2007]. The significance of this is unclear, but may point toward the two-component mixing model to explain the O isotopic composition of Solar System solids. The silicon isotopic composition of dust particles (likely sputtered by the solar wind) was measured by ROSINA for 67P/C-G. The Si isotopic composition shows a depletion of the heavy silicon isotopes ^{29}Si and ^{30} Si with respect to ^{28}Si and solar abundances [Rubin et al. 2017]. The origin of the heavy Si isotope depletion, still debated, could suggest a presolar signature in silicates present in dust particles.

Short lived radionuclides: ^{26}Al The short-lived radionuclide ^{26}Al was abundant in the early Solar System, with ^{26}Al / ^{27}Al ≈ 5.2 10^{-5} [Kita et al. 2013]. Its β-decay to ^{26}Mg (half-life 0.72 Myr, energy 4.0 MeV) was a significant source of heating, and probably played an important role in the internal heating and differentiation of early-forming planetesimals. Its presence as a live radioactivity in the nebula also allows dating of the formation of individual phases in meteorites with respect to the formation of CAIs, the earliest solids to have formed in the Solar System, although this dating technique requires that ^{26}Al was homogeneously distributed in the early protoplanetary disk [Kita et al. 2013]. Another limitation is also that suitable phases with high Al/Mg ratios, such as plagioclase, are required, so that the contribution of ^{26}Mg originating from the decay of ^{26}Al can be discriminated from the naturally occurring stable ^{26}Mg isotope. Unfortunately, more common phases such as olivine or enstatite are not suitable because of their low Al/Mg ratios. Al-Mg systematics have been measured in four 81P/Wild 2 particles [Matzel et al. 2010] [Ogliore et al. 2012] [Nakashima et al. 2015], and in all four cases no evidence of live ^{26}Al at the time of their crystallisation was found. If these formed after injection of ^{26}Al into the nebula, they must have formed > 3 Myr after meteoritic CAIs formed. An alternative explanation for this observation is that they formed before ^{26}Al injection into the nebula, or that ^{26}Al was not homogeneously distributed in the early protoplanetary disk. A late Mg isotopic exchange through metamorphism of chemical alteration also remain in the range of possibilities.

Noble gases—Stardust samples contain cometary light noble gases: He, Ne [Marty et al. 2008] [Palma et al. 2007] [Palma et al. 2013] [Palma et al. 2015]. Most of the noble gases were found in the wall of the Stardust tracks, probably carried by the fine-grained fraction of the particles. The concentrations of noble gases can be quite high, which may be consistent with formation in the inner Solar System and consequent exposure to high fluences of solar energetic particles. The ^{3}He / ^{4}He isotopic ratio lies between the solar wind value (post-D burning helium) and the protosolar nebula ratio. Hence the 81P/Wild 2 matter possibly was therefore exposed to the irradiation of the proto-Sun. The Ne isotopic composition of 81P/Wild 2 matter is compatible with that of Ne in chondrites, rather than being close to the solar composition.

3.5 Summary

Most information in this composition section derives either from samples returned from comet 81P/Wild 2 by the Stardust mission or 67P/C-G dust particles analyzed in situ by the Rosetta spacecraft. Despite the small size of the sample collection, the principal limitation in the analysis of 81P/Wild 2 samples returned by Stardust is instrumental. Some instruments now used routinely to analyze these samples did not exist at launch of the mission, e.g. nanoSIMS [Stadermann et al. 2008]. New laboratory analytical techniques that are just now being brought to bear on cometary dust particles include nanoFTIR [Dominguez et al. 2014], Atom Probe [Heck et al. 2014] and microbeam laser resonance ionization mass spectrometry such as CHILI (Chicago Instrument for Laser Ionization [Liu et al. 2017]). Focused-Ion Beam (FIB) is opening new windows also through dramatically improved sample preparation. With each improvement in analytical technique, and with each introduction of an entirely new technique, there is the potential for new discoveries in existing collections [Westphal et al. 2016].

The same kind of remark can be made regarding Rosetta data. Although providing unique information in the direct vicinity of the comet since 2014, one has to keep in mind that the instrumentation was selected in the mid 90’s on the basis of technology available at that time. Nonetheless a global composition of cometary particles can be derived from these data as is shown in Fig. 3. It shows that organic matter in an important component of the dust particles, however quantification of some elements (e.g. H and S) is still missing at the time of writing. The distribution of O between the mineral and the organic phase is still poorly constrained [Bardyn et al. 2017]. If one tries to estimate a distribution in volume of the mineral and organic components, as shown in Fig. 3 (c), one has to rely on a very rough estimation of the relative density (3 for minerals and 1 for the organic molecules [Robertson 2002]) which is subject to debate.

4 Physical Properties of Dust Particles

4.1 Morphology

The morphology of dust particles describes their structure and shape and how these emerge from the characteristics of the particle’s components. It is crucial to investigate as it is a key property to understand basic parameters of comets, such as porosity, strength and thermal properties. Polarimetric observations of comets suggested that the basic morphology of cometary dust is twofold, containing more compact entities, either particles or aggregates, and more porous aggregate particles (see Subsec. 1.2, Subsec. 4.2). Stardust [Brownlee 2014] brought the only available samples of cometary dust to Earth; although the majority of the particles were structurally altered during collection, it became evident that cometary dust consists of aggregates. The most accurate morphological analysis of cometary dust to date stems from Rosetta.

MIDAS provides topographic information on dust particles from 1 to 50 μm in size [Bentley et al. 2016], while COSIMA obtained resolved images of dust particles from 30 μm to 1 mm [Hilchenbach et al. 2016]. The dust particles investigated by MIDAS (Fig. 4) and COSIMA (Fig. 5) provide the least altered sampling of cometary dust over scales from 1 μm to 1 mm, as they were collected on their own target with relative velocities in the range from 1 to 15 m s^{-1} [Fulle et al. 2015a] at distances from the comet nucleus lower than 500 km [Bentley et al. 2016] [Merouane et al. 2016]. COSIMA provided evidence for break-up events of large parent particles. Indeed, large numbers of particles were collected during a single exposure (down to 1 day) by specific target areas with no collection on other target areas exposed at the same time [Merouane et al. 2016] [Langevin et al. 2017]. Particles are also likely to break-up and spread over the MIDAS targets upon collection [Bentley et al. 2016] [Ellerbroek et al. 2017].

The information obtained by COSIMA and MIDAS using two different approaches led to overall similar conclusions applying to a range of sizes of cometary dust extending over 3 orders of magnitudes. Both MIDAS [Bentley et al. 2016] and COSIMA [Langevin et al. 2016] identified particles with well-defined boundaries. Of these, the smallest individual particles detected with MIDAS are about 1 μm in size [Bentley et al. 2016] while the largest one identified by COSIMA is about 350 μm in size. Each of these particles exhibit textural substructure [Mannel et al. 2016] [Langevin et al. 2016], down to about 25 nm for MIDAS. Thus, they can be defined “compact aggregates” or eventually “compact particles” (left-hand panel of Fig. 4 and Fig. 5a). Many compact aggregates collected by COSIMA broke up into smaller components when analysed because of electrostatic forces [Hilchenbach et al. 2017]. The reason why no particle smaller than 1 μm has been detected by MIDAS could be due to a collection bias or to a dearth of such particles in the cometary environment [Bockelée-Morvan et al. 2017].

Most particles impacting COSIMA collection plates are destroyed into clusters of fragments, which exhibit morphologies ranging from sub-components connected by a matrix (Fig. 5.b) to rubble piles (Fig. 5.c) and shattered clusters (Fig. 5.d) with separated sub-components and a low height to size ratio (1:10). This range of morphologies can be attributed to a large extent to the relationship between the incoming velocity and the tensile strength of the particle [Hornung et al. 2016] [Ellerbroek et al. 2017]. There is continuity with compact aggregates, corresponding to a higher tensile strength to velocity ratio, as demonstrated by the break-up of such particles into rubble piles observed under the ion gun of COSIMA. Specular reflections observed by COSIMA may indicate that monocrystalline grains are likely to have been collected as part of large aggregates [Langevin et al. 2017].

The collected particles observed by MIDAS and COSIMA therefore provide evidence for textural complexity over a range of scales from 1 μm to 1 mm, of main importance for comparison with interplanetary dust particles and micrometeorites (as discussed in Subsec. 5.3). Porosity at such scales may be compared with the porosity of the nucleus, in the 60% to 80% range as deduced by the CONSERT experiment from the permittivity of the small lobe [Kofman et al. 2015] [Herique et al. 2016], thus contributing to the overall low density of 67P/C-G of about 530 kg m^{-3} [Pätzold et al. 2016] [Jorda et al. 2016]. The results of dust collection experiments MIDAS and COSIMA provide the first view of the hierarchical structure of dust in comets.

4.2 Dust Bulk Density and Microporosity

The interaction of photons with compact aggregates as observed by COSIMA is dominated by surface scattering. Conversely, the mean free path of photons in the clusters of fragments observed by COSIMA (Figs 5b, c, d) is in the range of 25 μm, indicating a microporosity > 50% [Langevin et al. 2017]. The particle collected by MIDAS that is presented in the right-hand panel of Fig. 4 has a even larger porosity: the underlying surface can be observed between subcomponents [Mannel et al. 2016]. The fractal dimension of the associated parent particle was determined via a density-density correlation function to be $D_f = 1.7 \pm 0.1$ [Mannel et al. 2016], which can be related to a volume filling factor φ (the fraction of volume occupied by matter) by $\varphi = (R/r)^{D_f - 3}$, where R and r are the volume-equivalent radii of the aggregate and of the grains composing the aggregate, respectively [Fulle and Blum 2017]. The microporosity, defined as $1 - \varphi$, is 99% for this MIDAS particle [Fulle and Blum 2017]. Here we define fluffy particles as those with a microporosity > 90%.

In the 67P/C-G coma, compact and fluffy particles are consistent with the morphology of aerogel tracks produced by high-speed impacts of 81P/Wild 2 particles observed by Stardust [Brownlee 2014]: carrot-like aerogel tracks (type A, 65% of the total number of tracks) produced by impacts of compact aggregates of minerals [Burchell et al. 2008], and bulbous tracks consistent with the explosion of fluffy aggregates in the aerogel [Trigo-Rodríguez et al. 2008]. Bulbous type-B tracks (33% of the tracks) show terminal particles, which are aggregates of minerals, lacking in bulbous type-C tracks, 2% of the tracks [Burchell et al. 2008]. GIADA confirms this scenario [Della Corte et al. 2015], observing dust belonging to two main families, compact (a) and fluffy (b) particles. (a) All compact particles provide a signal to the IS [Rotundi et al. 2015] and are consistent with Stardust type-A tracks.

Their internal tensile strength T is consistent with $log(T/1kPa) = 1.48\ \varphi - 0.2$ [Güttler et al. 2009], in agreement with the models of dust impacts on the COSIMA collection plate [Hornung et al. 2016]. Typical strengths of compact particles are $1 < T < 6$ kPa for $0.15 < \varphi < 0.66$, i.e. a microporosity between 34% and 85%. COSIMA has mostly observed compact particles (according to the definition above), which are porous aggregates fragmented on the instrument funnel and collection plates only [Merouane et al. 2016]. (b) The dust showers observed by GDS only are explained in terms of fractal aggregates of $D_f \leq 2$ fragmented at a few meters from the spacecraft [Fulle et al. 2015a]. About 30% of the observed GDS dust flux is observed in showers [Fulle and Blum 2017], and their parent fractal particles are consistent with type B and C tracks. The showers associated with a compact particle are consistent with type-B tracks [Fulle et al. 2016b]. A comparison with the relative occurrence of B and C tracks is impossible, because GIADA showers have a cross-section larger than GDS [Fulle and Blum 2017], so that the compact particles associated to a shower may not enter GDS and may have a momentum below the IS detection limit. Hugoniots (which provide the states on both sides of a shock wave in a one-dimensional deformation in solids) of hyper-velocity impacts by projectiles of density lower than the Stardust aerogel predict explosions inside the aerogel (as observed in tracks B and C) instead of surface craters [Knudson and Lemke 2013].

The GIADA measurements of both cross-section and mass for 271 compact particles (Fig. 6) has provided the average bulk density $\rho_d = 785^{+520}_{-115}$ kg m^{-3}, 1σ [Fulle et al. 2017]. The lower value estimated by COSIMA in the same size range covered by Fig. 6 is about 200 kg m^{-3} [Hornung et al. 2016]. This value has been inferred by impact models of particles porous enough to fragment on the COSIMA collection plate at the observed impact speed of a few m s^{-1}, so that this lower density refers to a subset of compact particles only, missing all densest ones [Fulle et al. 2018]. GIADA estimates an aspect ratio ≤ 5 of ≈ 98% of the compact particles (Fig. 6), consistent with the largest observed aspect ratio of 3.2 observed over 24 COSIMA compact particles. The low aspect ratio and rotating frequency of the particles make improbable dust fragmentation by centrifugal forces [Fulle et al. 2015b]. Coupled to the bulk density of the 67P/C-G nucleus [Pätzold et al. 2016] [Jorda et al. 2016], the average dust bulk density provides an average dust microporosity of 60%, i.e. $\varphi = 0.4$ [Fulle et al. 2017], affected (as well as the density) by a wide dispersion. The microporosity of compact aggregates does not reach anyway that of fluffy aggregates, always > 90% [Fulle and Blum 2017]. The average bulk density of 67P/C-G compacted and dried dust is 1925^{+2030}_{-560} kg m^{-3}, 1σ [Fulle et al. 2017]. Many particles have a bulk density > 4000 kg m^{-3}, i.e. are sub-mm aggregates of minerals with almost no porosity, which are consistent with the Stardust type-A tracks producing a single terminal particle [Burchell et al. 2008]. The minerals composing these sub-mm aggregates necessarily condensed in the inner solar nebula, thus confirming its complete mixing up to 30 au in the first Myr [Ciesla 2011], as already inferred from Stardust data [Brownlee 2014].

In contrast to Stardust, which supports a CI-chondritic composition [Brownlee 2014], the composition of 1P/Halley and 67P/C-G dust matches the carbon solar abundance [Lodders 2003] [Bardyn et al. 2017] [Jessberger 1989]. Then, the dust and nucleus bulk densities constrain the dust/ice mass ratio of the 67P/C-G nucleus and its average composition: (4 ±

1)% of sulfides, (20 ± 8)% of ices, (22 ± 2)% of silicates, and (54± 5)% of hydrocarbons, in volume abundances [Fulle et al. 2017]. This dust composition matches that measured by COSIMA, taking into account the uncertainties affecting the elemental abundances [Fulle et al. 2018]. The refractory/ices mass ratio in the nucleus is close to 7.5, implying a 67P/C-G water content lower than in CI-chondrites [Fulle 2017]. The average refractory/ices mass ratio in 67P/C-G dust is larger than the nucleus one, being about 20 [Fulle et al. 2017]. Since the dust cross-section in a coma is much larger than that of the sunlit nucleus, such a low ice content in dust is still consistent with the dominant water loss from dust observed e.g. in 103P/Hartley 2 [Fulle et al. 2016a].

4.3 Size Distributions

The range of sizes of dust particles detected by Rosetta in the coma was from 1 μm [Bentley et al. 2016] to about 1 m [Fulle et al. 2016c]. Evidence that individual sub-μm particles are present in comae is weak. For instance, the low-phase negative polarization and backscattering of dust comae [Hanner and Newburn 1989], are well fit by large (> 3 μm) fractal aggregates [Mann et al. 2004] [Kolokolova et al. 2004] [Levasseur-Regourd et al. 2008] [Lasue et al. 2009], as further discussed in Subsec. 5.2. The submicron-sized grains composing the dust aggregates, well sampled by Stardust in 81P/Wild 2 [Brownlee 2014] and MIDAS in 67P/C-G [Bentley et al. 2016], are linked by sticking strengths orders of magnitude larger than gas pressures in comae [Skorov and Blum 2012] [Gundlach et al. 2015]. Processes or mechanisms that might overcome these sticking forces in compact aggregates of size > 1 μm have not been proposed (see Subsec. 4.5). Most micron-sized MIDAS particles are interpreted as fragments of larger parent particles [Bentley et al. 2016], with a cut-off which seems to exclude any electrostatic bias (as detailed in Subsec. 4.5). The only measurements supporting the presence of single submicron-sized particles in comae are (i) the smallest non-clustered impact craters on the Al-foils of the Stardust mission [Hörz et al. 2006] – clusters of craters are another evidence of fluffy aggregates in 81P/Wild 2 – and (ii) two PIA data-point in 1P/Halley at mass < 10^{-15} kg [McDonnell et al. 1989]. The cumulative sub-micron size distribution inferred from the craters on the Stardust Al foils has a power index < 1.5 [Price et al. 2010], and therefore there is consistency between the observed flux of sub-micron particles and the fragmentation of incoming fractal parent particles of $D_f \leq 2$, as detailed in Subsec. 4.5. Fractal aggregates with $D_f < 2$ are optically thin, so that their optical, thermal and dynamical properties mostly mimic that of single submicron-sized grains [Bertini et al. 2007], explaining e.g. long dust tails and dust temperatures up to 500K at Sun distances > 1 au. The composition of the fractal aggregates affects the internal multi-scattering, i.e. the albedo of the aggregates [Bertini et al. 2007].

Dust fluences measured at comets 1P/Halley, 26P/Grigg-Skjellerup, 81P/Wild 2 and 9P/Tempel 1 were sampling dust masses > 10^{-15} kg, i.e. dust with $R > 0.7$ μm if $\rho_d \approx 800$ kg m^{-3}. They were converted to a dust mass distribution at the nucleus surface by means of isotropic models, but they provided unphysical results [Fulle et al. 1995] [Fulle et al. 2000] as confirmed by Rosetta data, which show that the dust subsolar ejection is an order of magnitude larger than at terminator [Della Corte et al. 2015]. Since dust in comets has a volume filling factor covering many orders of magnitude, unrealistic assumptions are needed to convert the momentum measured by flyby fluences into sizes. Rosetta was the first space mission to measure a reliable dust size distribution in a comet, because the Rosetta dust instruments (COSIMA, GIADA and MIDAS) have provided, for the first time, information on the microporosity of the collected particles. GIADA has observed showers of fluffy dust fragmented at a few meters from Rosetta [Fulle et al. 2015a]. Far from Rosetta, any significant (i.e. involving > 5% of the total ejected mass) dust fragmentation and sublimation in 67P/C-G coma are excluded by all available Rosetta data [Fulle et al. 2016a] [Moreno et al. 2017].

A summary of all the power indexes collected by GIADA, COSIMA, OSIRIS, ROLIS and ground-based observations is shown in Fig. 7. Before 2015 equinox, most dust is coming from Hapi, a dust deposit close to the northern pole. After the 2015 equinox, dust is coming from the erosion of meters around the southern pole, showing that the pristine dust has a power index close to −4 over all dust sizes. The size distribution characterises the relative abundance of particles of different sizes in an ensemble. If approximated by a power-law, the characteristic quantity is its exponent. The smaller the (negative) size distribution exponent, the stronger is the relative contribution of small particles. For exponents < −4, not only the cross-section, but also the mass is dominated by the smallest particles present. The mass is concentrated in the largest particles for exponents > −4, and for exponents > −3, also the cross-section is predominantly in the largest particles. This occurred before the 2015 equinox at sizes < 1 mm [Rotundi et al. 2015] [Fulle et al. 2016c] [Marschall et al. 2016] [Merouane et al. 2016], implying that most 67P/C-G dust coma light was scattered by mm-sized particles. Dust data collected after the 2016 equinox are too scarce to provide significant statistics. In most comets and in 67P/C-G, the differential dust size distribution has a power index shallower than −4 [Fulle 2004], so that the integrated dust mass loss depends always on the largest ejected chunk, which however remains unknown in most comets. At 67P/C-G, OSIRIS has observed the largest pebbles and chunks escaping the nucleus, of sizes ranging from about 1 cm at 3.5 au [Rotundi et al. 2015], up to about 1 meter at perihelion [Fulle et al. 2016c] [Ott et al. 2017]. The measurement of the ejected dust mass is complicated by the fact that some largest ejected chunks remain in metastable orbits around the nucleus up to the following perihelion passage [Fulle 1997] [Rotundi et al. 2015], while a significant fraction of the ejected mass falls back on the nucleus surface [Thomas et al. 2015a] [Pajola et al. 2017a] [Fulle et al. 2017]. The relationship between the size distribution of the ejected dust and that of the dust deposits is complex, and depends on the details of the fall-back processes and of the gas release from the deposits [Pajola et al. 2017a].

4.4 Optical and Thermal Properties

The phase curve of the diffuse coma observed by OSIRIS during observations covering phase angles from 0 to 155 deg within 2.5 hours seems inconsistent with the commonly adopted average cometary dust phase function [Kolokolova et al. 2004]. Such an OSIRIS dust phase function shows a stronger back-scattering than assumed so far [Bertini et al. 2017]. The OSIRIS dust phase function is consistent with most individual Earth-based or Earth-orbiting observations of comets. Observations by OSIRIS of dust bursts within 100 m from Rosetta suggest that the OSIRIS phase function is valid for dust sizes up to 2.5 mm [Fulle et al. 2018].

The diffuse coma has a color consistent with the average nucleus one at phase angles < 30 deg, and is significantly bluer above [Bertini et al. 2017]. The dust has a negligible phase reddening at phase angles < 90 deg, indicating a coma dominated by single scattering [Bertini et al. 2017]. The spectra of individual particles measured in the 535-882 nm range cover all the spectral slopes observed in the reddest and bluest nucleus areas [Frattin et al. 2017].

Dust in 67P/C-G coma shows a temperature a few per cents above the equilibrium one outside outbursts, but it increases up to factors 3-4 during outbursts, suggesting the ejection of smaller particles during outbursts [Bockelée-Morvan et al. 2017]. During steady activity, the inferred minor flux of fractal aggregates of $D_f < 2$ explains all the features of the IR coma spectra observed by VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) [Bockelée-Morvan et al. 2017]. The dust composition and physical properties discussed above seem consistent with these data, although scattering models fitting all the observations are still unavailable.

4.5 Charged Dust

The amount of electric charge collected by fluffy and sub-μm dust particles affects their motion in comae and tails and their lifetime against electrostatic fragmentation. The Rosetta mission provided the first direct evidence for the presence of electrically charged dust particles in a coma. These observations were possible as a result of the interaction between dust and the spacecraft electric potential, which was oscillating around −10 V [Nilsson et al. 2015] within 100 km from the 67P/C-G nucleus.

The fundamental physics of charged cometary dust has been studied for a long time [Mendis et al. 2013]. Dust charging is a delicate interplay between several currents, including electron and ion collection currents from the surrounding plasma, ultraviolet induced photoelectron currents, secondary electron emission (due to energetic ion and/or electron bombardment), thermo-ionic emission, field emission (due to large surface fields), etc. As a rule of thumb, a dust particle collects about 700 extra electrons per unit particle volume-equivalent radius (measured in μm) and unit electric potential difference between the particle surface and the surrounding plasma (measured in V). This means that in the solar wind a particle of 1 μm size can have about 10^4 extra electrons. Based on our experience with mesospheric dust charging at Earth it can be assumed that most of the extra electrons are deep inside the dust particle and they can electrostatically disrupt fluffy, highly friable dust particles [Hill and Mendis 1981]. An updated version [Mendis et al. 2013] predicts that a 10^{-19} kg particle can be electrostatically disrupted if its tensile strength is less than about 0.5 MPa. In general, the tensile strength of a particle charged at the potential U is $T = \epsilon_0/2\,(U/R)^2$ [Boehnhardt and Fechtig 1987]. Regarding dust electrical resistance, COSIMA estimates a specific resistance of 10^{16} ohm mm^2 m^{-1} after the interaction of an Indium ion beam with the particles [Hilchenbach et al. 2017].

The GIADA dust showers have been modelled in terms of cm-sized fluffy dust aggregates charged by the flux of secondary electrons from the spacecraft, so that they decrease their potential from $-2 < U < +2$ V in the coma to $-17 < U < -5$ V close to the spacecraft [Fulle et al. 2015a]. This potential decrease is sufficient to disrupt fractal particles (independent of their size if $D_f \approx 5/3$), because the tensile strength linking the grains of a dust aggregate is $T = 160\ [R/(1\mu m)]^{D_f - 11/3}$ Pa [Skorov and Blum 2012] [Fulle and Blum 2017]. The fragments are then decelerated by the electrostatic interaction between negatively charged fractal fragments and the spacecraft [Fulle et al. 2015a]. This model predicts a fractal dimension $D_f < 1.9$ [Fulle et al. 2016a] consistent with the measurements on the fluffy MIDAS particle, $D_f = 1.7 \pm 0.1$ [Mannel et al. 2016]. The dust is deflected away from Rosetta at a charge-to-mass ratio of about 1 C kg^{-1} [Fulle et al. 2015a]. This may explain the few MIDAS detections between 1 and 10 μm, with no submicron-sized samples, well above MIDAS resolution. However, most MIDAS detections are clustered, suggesting fragmentation of parent particles of size > 10 μm at the impact on the collection plate [Bentley et al. 2016]. Only compact particles with $R < 0.5$ μm have $q/m = 3\ \epsilon_0\ U/(\rho_d R^2) > 1$ C kg^{-1}, implying that sub-micron compact particles only could have been pushed away by the spacecraft potential. The GIADA and MIDAS sub-mm fractal fragments of $D_f < 2$, decelerated at speeds of about 1 cm s^{-1} by the spacecraft electric field, have a kinetic energy of 0.2-20 keV [Fulle et al. 2016a], so that the bursts of 0.2-20 keV electrons coming from the nucleus (direct dust) or from the Sun (dust reflected by the solar radiation pressure) measured by RPC/IES (Radio Plasma Consortium - Ion and Electron Sensor) on Rosetta [Burch et al. 2015] are not evidence of charged nano-dust.

These facts show that the electrostatic fragmentation of fractal aggregates of $D_f < 2$ is independent of their size and requires a dust charging much larger than occurring in the coma. Electrostatic forces may fragment only sub-micron sized compact particles. Fluffy particles carry always an important amount of charge vs. their mass, so that their motion is significantly affected by electric and magnetic fields, confirming the interpretations of striae in dust tails in terms of charged dust [Notni and Tiersch 1987].

4.6 Summary

Stardust and Rosetta have revealed extreme complexity in the physical properties of cometary dust. Dust particles are aggregates of grains, with volume filling factors covering many orders of magnitude. Cometary dust aggregates range from extremely compact to extremely fluffy. The most compact ones have shapes sometimes very far from spheres, and sub-mm thermally annealed aggregates of minerals observed both by Stardust and Rosetta suggest an origin in the inner protoplanetary disc. On the opposite end, Rosetta data suggest the presence of extremely fluffy aggregates of equivalent bulk density < 1 kg m^{-3}. Between these two extremes, the aggregates cover a wide range of porosities. Their hierarchical structure, clearly imaged by Rosetta for the first time, provides constraints to the processes of dust condensation in the protosolar nebula and the protoplanetary disc.

The complexity of the physical parameters describing cometary dust challenges the interpretation of data from flyby missions and ground-based observations, always based on multi-parametric models which are hard to constrain, because averaging is not a suitable way to define shape, equivalent bulk density and sizes, and because their distributions evolve in time according to nucleus seasons, as seen at Rosetta.

5 Discussion

5.1 Dust Release, Continuous and Abrupt Processes

The nucleus of a comet is the origin of dust seen in the inner coma and, ultimately, in the cometary dust tail and trail. However, the details of the processes that initially lift the dust are, at best, uncertain.

The brightness distributions of inner comae are characterized by maximum intensities in a direction approximately sunward [Keller et al. 1994]. This observed quasi-continuous emission is occasionally augmented by outburst phenomena, which are abrupt, short, and irregular events of mass loss. During the approach of the Deep Impact spacecraft to comet 9P/Tempel 1, outbursts were repeatedly observed [A’Hearn et al. 2005] while the rendezvous of Rosetta with comet 67P/C-G provided 26 months of monitoring during which an outburst was observed once in April 2014, followed by observations at increased frequency after May 2015 at all observed heliocentric distances. Outbursts were seen on a daily basis around the perihelion passage [Vincent et al. 2016a].

The largest liftable particle radius is usually given as $R = 3\, C_D\, Z\, u_0\, R_n^2 \,/\, (8\, GM\, \rho_d)$, where R_n is the nucleus radius, GM is the standard gravitational parameter (using the mass of the comet), Z is the surface gas mass flux, u_0 is the velocity of the gas at the surface, C_D is the gas drag efficiency, and ρ_d the dust bulk density [Gombosi and Horanyi 1986] [Harmon et al. 2004]. u_0 is usually taken as the thermal expansion velocity at the surface multiplied a correction factor of order of 9/4 [Finson and Probstein 1968]. Typical values for R are of the order of a centimetre. This equation, coming from the balance between gas drag and gravity at the surface, has been widely used to explain particle mass loss from the sub-micron to the millimetre range with H_2 O being the driving volatile at heliocentric distances of less than about 2.7 AU. On the other hand, the observations of 67P/C-G suggest ejection of particles much larger than could be explained by this equation [Fulle et al. 2016c] [Ott et al. 2017].

Outbursts are indicative of a rapid release of large amounts of gas, which presumably would allow larger chunks to be ejected. It is important to note that the driving volatile initiating the outburst may not be H_2O but possibly more volatile species close to the surface and heated via conduction through the surface layer. On the other hand, with the exception of very specific cases [Montalto et al. 2008], even the larger outbursts are not the dominant source of dust in the coma. Most of the comae observed during flybys and that of 67P/C-G show stable dust coma brightness distributions on timescales of 1/10th to 1/20th of a rotation period. Hence, it remains appropriate to treat the continuous, more stable, emission separately from the more abrupt, short duration, outbursts and to assess their source processes. We look at the continuous emission first.

It might be assumed that a more uniform, apparently insolation-driven emission from much of the nucleus surface would be a straightforward assumption on the basis of observations of the inner comae of several comets. This would be H_2O driven and controlled through the largest liftable mass. However, this assumption is surprisingly simple to challenge. In the largest liftable mass calculation, van der Waals (vdW) forces are ignored but simple calculations [Kührt and Keller 1996] show that for micron-sized particles the cohesive forces can exceed vapour pressure forces by several orders of magnitude [Skorov and Blum 2012] [Gundlach et al. 2015]. Hence, there is inconsistency in a simple model of the dust ejection process with a size distribution extending from sub-micron particles (as seen at 1P/Halley, for example) to decimetre-sized chunks (as indicated at 67P/C-G).

It is also highly questionable whether dust emission is solely insolation-driven. More localized emission may give the appearance of being uniform and insolation-driven as a result of gas drag and lateral gas flow. This has been tested by fits to the gas densities measured at 67P/C-G.

Initial fits [Bieler et al. 2015] [Marschall et al. 2016] [Fougere et al. 2016] were consistent in showing the dominance of one particular area (Hapi) during the early phase of the Rosetta mission. Other work has gone further by testing even more localized emission distributions. For example, an insolation-driven model and a model where “cliffs” (topographic slopes of greater than 30 degrees) were active together with emission from the Hapi region (between the two lobes) of the nucleus were compared by [Marschall et al. 2017]. An active “cliff” hypothesis had been favoured on the basis of OSIRIS observations [Vincent et al. 2016b]. The fits were statistically identical. The cliff hypothesis removes issues with cohesive forces where gravity is sufficient to breach the vdW forces but it requires steady activity from these specific sites if it is a dominant mechanism. It is also inconsistent with dominant dust ejection from a dust deposit (Hapi), and with observations of surface changes in flat dusty regions (i.e., Imhotep, Ash, and Anubis) of the nucleus that we must assume are activity driven [Auger et al. 2015] [El-Maarry et al. 2017], although even here it is not proven that dust has actually been ejected from some of these sites. Hence, there is still no indisputable conclusion on the source distribution on the nucleus and the geomorphology of the source. This dramatically reduces our ability to constrain source processes and this is further hindered by the apparent absence of ices directly at the surface.

[Sunshine et al. 2005] demonstrated that the surface area of H_2O ice on a cometary nucleus is insufficient to provide the measured gas production rates even in the case of free sublimation. Hence, a concept where H_2O ice just below a (partially) desiccated, weakly bound, layer of refractory material needs to be conceived that also resolves the problem with vdW forces. Some mechanisms may plausibly resolve this issue but are difficult to prove. Some examples include i) refractory particles being separated from each other by an icy “glue” [Houpis et al. 1985] that sublimes to release the particles without a vdW interaction, ii) small scale trapping of ices to produces smaller “explosions” on unresolved scales, iii) electrostatic lifting to break vdW forces (see Subsec. 4.5). Neither computer nor laboratory simulations of these processes have been presented. However, even in the case of the electrostatic mechanism, some circumstantial evidence can be found. For example, 67P/C-G shows ponded deposits [Thomas et al. 2015b] that are also seen on asteroids and have been attributed to the effect of electrostatic forces [Hartzell et al. 2013].

The causes of cometary outbursts have been the subject of research for many decades [Hughes 1990], but remain unresolved. Outbursts observed at 67P/C-G near perihelion cluster around local sunrise and early afternoon [Vincent et al. 2016a]. These authors infer that at least two different outburst mechanisms occur in 67P/C-G, attributing the morning events to near-surface thermal stress during the fast temperature rise, and the afternoon events to a process in a deeper layer that would be reached by the diurnal heatwave around that time. The typical mass ejected during a bright, spacecraft-detected outburst is of order 10^3 to 10^5 kg [Knollenberg et al. 2016] [Vincent et al. 2016a] [Grün et al. 2016] [Agarwal et al 2017]. Assuming that, during the 2016 perihelion of 67P/C-G, an average 10^4 kg per day were emitted during outbursts, this would only be a negligible fraction of the total dust production rate of > 1500 kg s^{-1} [Fulle et al. 2016c] [Ott et al. 2017].

The high nucleus porosity and its high dust-to-ice mass ratio might appear inconsistent with models involving the presence of sealed, pressurised cavities close to the surface that will release a large amount of gas and dust in a short time when opened [Belton et al. 2008] [Ipatov et al. 2011] [Belton et al. 2013]. However, combinations of different volatiles with differing sublimation temperatures offer a large number of possible alternatives. The crystallisation of amorphous water ice has been proposed as an energy source for cometary outbursts [Prialnik and Bar-Nun 1992] [Belton et al. 2008], and as a source of super-volatiles trapped in the amorphous matrix before. However, only the phase transition of pure amorphous ice is exothermic, any pollution by super-volatiles makes it endothermic [Kouchi and Sirono 2001]. Also the destabilisation of clathrates and release of trapped volatiles has been suggested to fuel outbursts from sealed sub-surface cavities [Mousis et al. 2015]. An alternative scenario ascribes dust outbursts to the deepening of pre-existing cracks under thermal stress to depths where pristine, super-volatiles are present that violently sublimate for a short time when first exposed to sunlight [Skorov et al. 2016].

In summary, the simplistic model of dust production resulting from gas drag overcoming gravity is no longer tenable. However, the dominant mechanism is still unclear. While activity from “cliffs” has been observed by Rosetta [Vincent et al. 2016a] [Pajola et al. 2017b], it remains difficult to prove that it dominates the emission. The relationship of the uppermost (optically visible) surface to icy material just below the surface and the means of releasing the dust component remains a subject of speculation. Outburst phenomena are of interest as a means of lifting large chunks of material but it appears proven that the outbursts observed and quantified at 67P/C-G do not dominate the total visible particle emission of the comet. The exact mechanism is unknown and multiple mechanisms cannot be ruled out.

5.2 Comparison Between Dust Properties and Clues From Light Scattering Observations

While unique space missions to a few comets are now revealing the properties of dust particles, a large amount of information on cometary dust is in the form of remote sensing data, collected by telescopes from the ground or in Earth orbit. The interpretation of these datasets to retrieve the physico-chemical properties of cometary dust is not straightforward and requires experimental and numerical simulations.

Laboratory studies—Measurements performed in the laboratory on analogues are mandatory to interpret properly the observational data and understand the chemical composition (content and nature of organic molecules, minerals and ices) and the physical properties (particle size, shape, structure etc.) of the dust emitted by comets (e.g., Levasseur-Regourd et al., 2007).

Observations of the thermal infrared spectral energy distributions (SEDs) within comae allow the characterization of cometary dust, as observed from Spitzer after Deep Impact hit 9P/Tempel 1 [Lisse et al. 2006] [Lisse et al. 2007]. The interpretation of SEDs strongly relies on laboratory measurements of the thermal emissivity of powdered compounds relevant in terms of analogues for dust in comets, such as minerals, carbonaceous compounds and ices, essential to infer the composition, temperature, size distribution and porosity of the dust [Wooden 2008].

Light scattering observations of comets, and especially their linear polarization, provide information on cometary dust, as already presented in Subsec. 1.2. The variations of the polarization with the phase angle and the wavelength are extensively studied in the laboratory on cometary dust analogues to point out comparisons with observations. Figure 8 presents instruments measuring the light scattering properties of randomly-oriented dust particles in suspension. PROGRA[2] corresponds to a series of gonio-polarimeters operating either in the laboratory under an air-draught technique for particles below about 10 μm, or under microgravity conditions during parabolic flight campaigns [Levasseur-Regourd et al. 1996] [Levasseur-Regourd and Hadamcik 2003] [Hadamcik et al. 2009a] [Levasseur-Regourd et al. 2015]. CODULAB, adapted from a previous instrument [Hovenier and Muñoz 2009], measures the Stokes parameters of dust particles in levitation under a gas flow [Muñoz et al. 2011] [Muñoz et al. 2012] [Muñoz et al. 2015].

The polarimetric phase curves of cometary analogues made of porous aggregates of sub-micron-sized Mg-silicates, Fe-silicates and carbon black grains mixed with compact Mg-silicates grains measured with these setups were found comparable to those observed on comae of comets [Hadamcik et al. 2007]. Submicron-sized grains in aggregates best fit the higher polarization observed in cometary jets and after fragmentation or disruption events, while a mixture of porous aggregates and compact grains was needed to fit whole comae observations [Hadamcik et al. 2006]. The influence of the size of dust grains (from nm to μm) and agglomerates (from μm to μm) on the maximum polarization of phase curves has been studied [Hadamcik et al. 2009b], allowing the interpretation of polarimetric images of the coma of 103P/Hartley 2 in term of progressive ice sublimation and sequences of particles fragmentation with increasing distance from the nucleus [Hadamcik et al. 2013]. Comparison of observations and laboratory measurements indicate that, at least for some comets, compact particles may dominate the polarization [Muñoz et al. 2015].

Complementary to the interpretation of coma observations, laboratory experiments are used to study the surface and subsurface of comets, where cometary dust may be formed, deposited and eventually ejected [Kochan et al. 1999] [Poch et al. 2016] [Jost et al. 2017] [Brouet et al. 2017].

Numerical simulations—Numerical simulations can complement the laboratory studies by reproducing and validating their results, by increasing the range of experimental conditions available and by confirming the physical interpretations of the properties necessary to reproduce the observations. Whenever intensity and polarization phase curves are obtained on a large enough range of phase angles and at different wavelengths, numerical and experimental simulations may be combined to infer some average properties, such as size and size distribution, ratio between transparent materials and absorbing materials (similar to dark organics), and ratio between fluffy aggregates and compact particles [Levasseur-Regourd et al. 2008] [Lasue et al. 2009] [Zubko 2012] [Hines and Levasseur-Regourd 2016]. Compact aggregates usually have a fractal dimension close to 3 and a porosity close to 75% [Bertini et al. 2009], while fluffy aggregates include many voids that translate into a large porosity (> 90% for $D_f \approx 2$, [Bertini et al. 2009]), which can be obtained in several ways, either by including voids in particles [Zubko 2012] or by considering specific fractal aggregation processes (see e.g. [Levasseur-Regourd et al. 2007] [Blum and Wurm 2008]).

Numerous authors have tried to constrain the scattering properties of cometary dust. It was first demonstrated that spheres or spheroids cannot, even with various size distributions and compositions, reproduce the observational data (e.g., [Kolokolova et al. 2007] and references within). With the development of more versatile T-matrix codes and Discrete Dipole Approximation techniques, models with aggregates of smaller particles were developed and found to provide satisfactory results (e.g. part 7 of [Kiselev et al. 2015] review). From combined numerical simulations of polarization data and silicate emission features, [Kolokolova et al. 2007] concluded that the dust in cometary comae presenting a high maximum in polarization consists of highly porous aggregates that may be associated with fresh dust as in new comets. The dust in comets with a lower maximum polarization consists of less porous particles which may be associated with more highly processed dust such as expected for the surfaces of Jupiter Family comets. However, recent simulations strongly suggest that cometary dust is a mixture of aggregates and of compact particles of varying absorption properties [Lasue and Levasseur-Regourd 2006] [Lasue et al. 2009].

Comparison with Rosetta ground-truth—Rosetta data have established, within the coma and nucleus of 67P/C-G, that the relative abundance of organics in dust is large (about 70% of the total volume, Sec. 3). It has also shown that the dust particles, the size distribution of which may vary, are irregular aggregates, some of them extremely fluffy and other ones extremely compact (Sec. 4). Such observational facts fit very nicely the clues derived from experimental and numerical simulations, once it is noticed that extremely compact aggregates may, from a light scattering point of view, behave like compact particles. The composition, size and structure of dust particles need to be taken into account to interpret the observations [Kolokolova et al. 2017].

While it is quite unlikely that future space missions will rendezvous numerous comets, remote observations of comets, complemented by elaborate experimental and numerical simulations, may thus be a unique approach to study the diversity of dust in comets.

5.3 Comparison Between Properties of Cometary Dust and of Some IDPs and Micrometeorites

Cosmic dust link with cometary sources—Every year, the Earth accretes about 4×10^4 tons of extraterrestrial material less than 1 mm in size on its surface (e.g. [Love and Brownlee 1993]). These dust particles originate from active comets, from asteroids and may also be coming from interstellar space for the very small particles (for a review, see [Brownlee 1985] [Rietmeijer 1998] and references therein).

While the exact origin of interplanetary dust accreted by the Earth is unknown, a significant contribution from cometary dust particles is expected, not only from comparisons between orbits of meteors and comets (e.g., [Jennsiskens 2006]), but also from classical meteoroids models based on dust impacts in the Solar System [Grün et al. 1985] [Divine 1993]. Recent work on dust particle dynamics and observations also tend to estimate that a major fraction of the small dust particles is dominated by dust from active comets (from 70 to 90% [Lasue et al. 2007] [Nesvorny et al. 2010] [Rowan-Robinson and May 2013] [Poppe 2016]).

Cosmic dust is mostly collected in the Earths stratosphere by NASA for small particles ranging from 1 to 50 μm (IDPs for “Interplanetary Dust Particles”, [Brownlee 1985]) and in polar caps as “MicroMeteorites” (MMs) in the size ranges from about 20 to > 400 μm (e.g. [Maurette et al. 1991] [Duprat et al. 2007] [Noguchi et al. 2015] [Taylor et al. 2016] [Rochette et al. 2008]). Chondritic porous IDPs (CP-IDPs) collected from the stratosphere [Ishii et al. 2008a] and ultracarbonaceous Antarctic micrometeorites (UCAMMs) [Nakamura et al. 2005] [Duprat et al. 2010] are proposed to be of cometary origin. Given that a significant portion of the interplanetary dust particles come from active comets, it is reasonable to compare their properties with the ones measured at comets, keeping in mind the expected differences due to sampling biases and alteration of the material.

Comparison of optical properties and particles morphologies—The observational properties of the interplanetary dust cloud suggest compositions of silicates and carbon compounds similar to cometary dust particles [Fixsen and Dwek 2002] [Reach et al. 2003]; the properties from linear and circular polarization of light scattered by interplanetary dust, i.e. zodiacal light, suggest an albedo about 6% at 1 au ([Levasseur-Regourd et al. 2001] [Lasue et al. 2015] and references therein). The reflectivity of cometary dust particles from 67P/C-G was estimated from COSIMA on Rosetta to be between 3% and 23%, depending on the type of particle [Langevin et al. 2017]. CP-IDPs are optically black [Brownlee 1985], with reflectivity < 15% over the visible range [Bradley et al. 1996]. The reflectivity of unmelted MMs has not been measured, but they appear as black objects as well.

Optical properties of the zodiacal light indicate that it originates from sunlight scattered by irregular dust particles of a few microns to several tens of microns in size. The fact that cometary dust particles are constituted of irregular fluffy and compact dust particles has been established from the results obtained with the Stardust samples [Hörz et al. 2006] [Burchell et al. 2008] and the in-situ studies performed by Rosetta. Cometary dust is therefore inferred to be compact or fluffy and constituted of subcomponents that can be fragmented down to the micrometer scale [Rotundi et al. 2015] [Langevin et al. 2016] or even lower [Bentley et al. 2016] [Mannel et al. 2016]; for details, see Sec. 4.

Analysis of the Stardust aerogel tracks showed the typical size range of dust particles collected from 81P/Wild 2 to be between 5 and 25 μm. These particles are a mixture of compact and cohesive grains (65%) and friable less cohesive aggregated structures (35%) with constituent grains of a size less than 1 μm and a size distribution consistent with the ones derived in the comae of comets [Hörz et al. 2006]. The typology of fragmented dust particles found by Rosetta is similar to some of the structures obtained on CP-IDPs, which have a similar tendency to fragment upon collection, and appear constituted mainly of submicrometer-sized components [Brownlee 1985]. Similarly, UCAMMs with a size ranging from 20 to 200 μm exhibit substructure down to the 50 nm scale, with a relatively tight packing of sub-components [Engrand and Maurette 1998] [Dobrica et al. 2012]. The morphology of the particles collected is illustrated in Fig. 9, the similarity between such particles and the ones collected and those analysed by Stardust and Rosetta is apparent.

Comparison of elemental composition and mineralogy—Most cosmic dust particles have undifferentiated (chondritic-like) bulk elemental compositions close to CI and CM meteorites (about 2% of falls), different from the more common ordinary chondrites (> 80% of falls) [Kurat et al. 1994] [Taylor et al. 2016] [Brownlee 2016] [Flynn et al. 2016]. Some dust particles, like ultracarbonaceous particles, do not even have meteoritic counterparts. These compositions are compatible with that of Stardust samples and of 67P/C-G (see Sec. 3).

The mineralogy of CP-IDPs, MMs and UCAMMs (crystalline silicates dominated by olivine, low-Ca pyroxene, and Fe-Ni sulfides is compatible with that of Stardust particles, although the Fe-Mg range of ferromagnesian silicates in 67P/C-G appears larger than for other comets [Zolensky et al. 2008] [Frank et al. 2014]. The range of olivine and low-Ca pyroxene compositions indicates a wide range of formation conditions, reflecting a large scale mixing between the inner and outer protoplanetary disk [Zolensky et al. 2006] [Ishii et al. 2008b] [Frank et al. 2014]. The pyroxene to olivine abundance ratio in CP-IDPs and UCAMMs is on average larger than 1, similar to 81P/Wild 2 samples. The presence of glassy phases like GEMS [Bradley 2013] in Stardust samples is difficult to assess, as GEMSlike material was created during capture by melting and intermixing of aerogel with crystalline minerals. Some GEMS inclusions might however be genuine [Gainsforth et al. 2016], but no enstatite whiskers or platelets, like the ones in CP-IDPs, were identified in Wild 2 samples [Ishii et al. 2008b].

Hydrous silicates have not been identified in Stardust samples, which suggests a lack of aqueous processing of 81P/Wild 2 dust [Keller et al. 2006] [Zolensky et al. 2008]. However, [Berger et al. 2011] found several sulfides (e.g. cubanite) in Stardust samples, which were interpreted as evidence for low-temperature hydrothermal processing in 81P/Wild 2, or on a parent body prior to the incorporation of these minerals in 81P/Wild 2. No hydrated minerals have been found in the anhydrous CP-IDPs, nor in UCAMMs. Small Mg-carbonates, similar to the ones identified in CP-IDPs [Flynn et al. 2009b] were identified in Stardust samples.

Comparison of carbon content and isotopic composition—CP-IDPs and UCAMMs are enriched in carbon with regard to the chondritic composition [Schramm et al. 1989] [Bradley et al. 1989] [Thomas et al. 1993] [Dartois et al. 2017]. The mean C/Si elemental ratio of CP-IDPs is about 7 times larger than the CI chondrite Orgueil [Thomas et al. 1993]. In UCAMMs the C/Si ratio vary from about 50 times CI up to several hundred times the chondritic ratio. Refractory organics in IDPs and UCAMMs can be mixed with rocky components, and constitute a matrix gluing the different minerals [Flynn et al. 2003] [Flynn et al. 2013] [Dobrica et al. 2012] [Charon et al. 2017]. They can also coat the dust grains [Flynn et al. 2013], a process possibly having taken place in the interstellar medium [Greenberg and Hage 1990] or in the Solar protoplanetary disk [Ciesla and Sandford 2012]. The major fraction of carbon consists of polyaromatic organic matter often exhibiting isotopically anomalous H and N (e.g. [Floss et al. 2004] [Duprat et al. 2010] [Bardin et al. 2015]). The observed large enrichments in D and ^{15} N can stem from cold chemistry processes at work in the presolar dust cloud which formed our Solar System, or in the cold regions of the early protoplanetary disk (for a review see [Sandford et al. 2016]).

The organic compounds in Stardust samples are rather scarce, possibly as a result of the harsh collection conditions that destroyed the most thermally unstable phases. Some organic phases are however indigenous to the comet and possess the same kind of polyaromatic composition [De Gregorio et al. 2011]. Isotopic anomalies in the H and N compositions are observed in Stardust samples like in the organic matter from CP-IDPs and UCAMMs [Sandford et al. 2006] [Matrajt et al. 2008] [De Gregorio et al. 2011] [Duprat et al. 2014]. Results from Rosetta show carbon enrichment in the dust fraction of the comet probably due to high molecular weight organic matter [Fray et al. 2016] [Herique et al. 2016] [Bardyn et al. 2017]. It is however difficult to assess for the time being whether the isotopic composition of organic matter in 67P/C-G is consistent with the variations measured for CP-IDPs and MMs.

Many CP-IDPs also contain sub-μm sized isotopically anomalous minerals, which represent circumstellar dust predating the formation of the Solar System. These pre-solar grains are found on average at the level of ≈ 500 ppm in CP-IDPs and UCAMMs, with up to concentrations of ≈ 1% in some IDPs (e.g. [Floss and Haenecour 2016] [Busemann et al. 2009], [Davidson et al. 2012] [Kakazu et al. 2014]). These values exceed that of the most primitive meteorites, which have pre-solar grain abundances of a few 100 ppm (e.g. [Nguyen et al. 2007] [Nguyen et al. 2010]). Analysis of the Stardust samples have shown that the concentration of presolar material within the solid fraction of 81P/Wild 2 is about 600 ppm (after correction from possible destruction upon collection), consistent with the average concentration measured in CP-IDPs [Floss et al. 2013].

To summarize, in the least altered IDPs and micrometeorites, the presence of vapor-deposited minerals, abundant organic matter, sub-grains of interstellar materials with strong isotopic anomalies, and both high and low-temperature nebular solids indicate that these particles are pristine, extraterrestrial materials. Their porous fragile structures and their nonhomogeneous compositions suggest that they have not been processed in large objects. Their similarity to cometary dust material studied by Stardust and Rosetta indicates a possible link to primitive icy bodies as a source for these dust particles.

5.4 Possible Clues on Origin of Dust in Comets

According to gravitational instability models of proto-planetary discs, the 67P/C-G nucleus is probably a mixture of pristine pebbles (the sources of compact and porous particles), and pre-solar fractals of $D_f < 2$ stored in the voids among pebbles [Mannel et al. 2016]

[Fulle et al. 2016b] [Fulle and Blum 2017] [Blum et al. 2017] [Barucci and Fulchignoni 2017]. Submicron-sized grains were accreted into cm-sized fractal aggregates of $D_f < 2$ in the protosolar nebula at collision speeds < 1 mm s^{-1} [Blum 2000] and later compacted into cm-sized pebbles in the protoplanetary disc at collisions speeds < 1m s^{-1} [Zsom et al. 2010] well before comets were formed [Fulle and Blum 2017] [Blum et al. 2017]. Fractal aggregates of $D_f < 2$ are expected to fill about 37% of the nucleus volume [Fulle and Blum 2017], in agreement with the percentage of the type B+C bulbous tracks observed in the Stardust aerogel, 35% of the total tracks [Burchell et al. 2008], and the rate of GI-ADA showers, about 30% of the GDS detections [Fulle and Blum 2017]. Within this scenario, cometary nuclei are statistically homogeneous bodies, so that their erosion provides dust fluxes proportional to the volume abundances of pebbles and fractals.

Pebbles, coming from the compaction by bouncing collisions of pre-solar fractals in the protoplanetary disc, are expected to have a microporosity [Zsom et al. 2010] matching that inferred by GIADA (close to 50%); the dust microporosity measured by GIADA is larger than in the pebbles because many dust voids may be filled by ices in the nucleus pebbles [Fulle et al. 2017]. Above the pebble size, the bouncing barrier in the protoplanetary disk may have stopped any further hierarchical structure [Zsom et al. 2010]. In this case, the results of dust collection experiments, MIDAS and COSIMA, suggesting a hierarchical structure of dust, cannot be extended to larger chunks observed by the imaging cameras of the Rosetta spacecraft and its Philae lander. If the comet nucleus is composed of cm-sized pebbles [Blum et al. 2017] [Fulle and Blum 2017], then the dust bulk density should show a discontinuity at the pebbles size, because it should depend on the microporosity only at smaller sizes, and on both the micro- and macroporosity, expected to be ≈ 40% [Fulle et al. 2016b] [Blum et al. 2017] [Fulle and Blum 2017] at larger ones. Regarding the mineral composition, the in depth analysis of the Stardust samples revealed that the dust particles of comet 81P/Wild 2 are an aggregate of material that has been heated at rather high temperature in the inner protosolar nebula and material that has always remained in the outer regions of the Solar System at rather cold temperature. The sub-mm and dense GIADA samples (left-hand data in Fig. 6) suggest as well the presence of aggregates heated in the inner protoplanetary disc. This shows that comets incorporated minerals with various histories and is a signature of a very complex mixing of processed material at the formation of our Solar System.

Regarding the organic composition of the cometary dust particles, putting aside the 81P/Wild 2 particles, for which the carbonaceous content could not be properly quantified, and keeping in mind that the quantification of this organic refractory phase has only been made in two comets (1P/Halley and 67P/C-G), one can derive as a general conclusion that comets are an important reservoir of carbon and organic matter in the Solar System. The refractory organic phase in cometary particles is dominated by a high molecular weight organic component, the actual structure of which bears similarities with insoluble organic matter extracted from carbonaceous chondrites. Such a high molecular weight material has probably been the form under which a large proportion of carbon has been delivered to Earth, as discussed in the next Subsection.

5.5 Possible Clues to Early Delivery of Complex Organics to Telluric Planets

As mentioned in Subsec. 5.3, the Earth's accretion rate of interplanetary dust is nowadays of about 40,000 tons per year, and a significant proportion of it is cometary dust. In the Late Heavy Bombardment (LHB) epoch, the spatial density of dust in the inner interplanetary dust cloud was orders of magnitude greater than today, and the brightness of the resulting zodiacal light was possibly more than 10^4 times higher [Nesvorny et al. 2010]. Given the composition and morphology of cometary dust particles, which present significant carbon enrichments and porosities (Sec. 3 and 4), their accretion on early telluric planets could have enhanced the delivery of prebiotic material, generating conditions favourable for the emergence of life [Elsila et al. 2009] [Altwegg et al. 2016]. The morphology of cometary dust particles, which are irregular and consist of low-density aggregates (Subsec. 4.1 and 4.2), may have allowed their temperatures to remain low enough to enable the survival of significant amounts of organics in the atmosphere.

The theory of meteoritic ablation during atmospheric entry, including the effects of thermal radiation, heat capacity and deceleration for solid particles, has been described in a number of publications (e.g. for a review [Jennsiskens 2006]). Assuming, as a first approximation, the transfer heat coefficient and the emissivity to be equal to unity [Jones and Kaiser 1966] and a typical particle to be small enough to reach a uniform temperature [Murad 2001], the relationship between the heat transfer from atmospheric molecules to the particle and the light emission and heating of the particle, under thermal equilibrium, leads to a surface temperature of the particle T approximated by $T^4 \approx (V_E \rho_a)/(\sigma_S \xi)$, where V_E represents the entry velocity of the particle, ρ_a the atmospheric density at the considered altitude, σ_S the Stefan constant and ξ the ratio of the total surface of the particle to its projected surface. For spherical particles $\xi = 4$, while it can be 1.7 times higher for spheroidal particles (oblate with a ratio of semi major axes of 2) and even $\approx \pi$ times higher for aggregated fractal particles [Meakin and Donn 1988]. Given that the material sublimation temperature could be about 2100 K (typical for rocks and metal, [Öpik 1958]) and the entry velocity should be about 30 km s^{-1} on average, then the altitude where sublimation starts is about 100, 97 and 93 km respectively for a sphere, a spheroidal particle and an aggregated fractal particle entering the Earth's atmosphere. Furthermore, the deceleration of the particle from collisions with the atmospheric molecules should also be taken into account. Assuming that they stick to the particle and thus transmit all their momentum to it, the maximum value of the temperature and thus the critical radius of the particles that may enter the atmosphere of Earth without being completely ablated can be determined [Jones and Kaiser 1966]. The effect of the particles' shape on the equilibrium temperature reached during atmospheric entry can be seen in Fig. 10. While the radius for which spherical particles reach the ground without being ablated is about 3.8 μm, the largest equivalent volume radius of irregularly shaped particles can reach up to 12 μm. All parameters staying the same, fluffy aggregates, which are the most efficiently decelerated particles, may bring up to π^3 times more material in volume without being ablated to the Earth's surface than compact spherical particles [Levasseur-Regourd and Lasue 2011]. For particles larger than a few tens of μm, thermal gradients can be observed inside the particles, indicating that thermal equilibrium was not reached during atmospheric entry heating, probably because of the short duration of the heating event [Genge et al. 2008]. In that case it is not trivial to model the proportion of material that would survive atmospheric entry, but measurements of the cosmic dust flux on Earth (e.g. [Taylor et al. 1998] [Duprat et al. 2001] [Plane 2012]) suggest that ≈ 80% of the mass of the incoming flux is vaporized upon atmospheric entry, the remaining 20% reaching the Earth as unmelted particles for ≈ 40% of them, the remaining ≈ 60% being partially melted or fully melted (e.g. [Dobrica et al. 2010]).

The increased density of interplanetary dust in the LHB epoch may have significantly increased the amount of cometary dust entering the Earth's atmosphere. It cannot be excluded that a significant proportion of the particles would, because of their structure, have brought pristine carbonaceous compounds from comets to the surface of early Earth; it may even be speculated that they could have contributed to the origins of life on our planet.

6 Conclusions and Open Questions

Our understanding of cometary dust, thanks to space missions to comets, to remote observations, to theoretical studies and to laboratory experiments, has remarkably progressed. However, as anticipated by [A'Hearn 2017], "As we have dramatically increased our knowledge, we have also opened up many new questions".

It is now recognized that the refractory organic phase in cometary dust is dominated by high molecular weight organic components and that comets are an important reservoir of carbon and organic matter; they could have delivered a significant amount of complex organic components to the Earth, about 4 Ga ago. This hypothesis is strongly reinforced by the evidence that dust particles within many comets are aggregates of grains, with morphologies ranging from extremely porous to extremely compact, and volume filling factors covering many orders of magnitude; their hierarchical structure has been clearly imaged by the Rosetta mission. It may be suggested, from the composition and physical properties of cometary dust particles, that they are aggregates of material from the outer regions of the Solar System mixed with material reprocessed in the inner protosolar nebula and transported to the outer regions of the protoplanetary disk. They are likely to be the most pristine solid matter available from the early stages of its formation. Studies of dust in comets provide constraints to the processes of dust condensation in the protosolar nebula and the protoplanetary disk.

Some exciting and fascinating results, already obtained about the composition and physical properties of dust in comets are opening new questions. First, is the composition of the dust released by the nucleus perfectly representative of the bulk composition of the dust deep inside it, and how could the organic high molecular weight component be better characterized? How are organic and inorganic phases related inside cometary dust? Secondly, what are the smallest grains or monomers building cometary dust aggregates, and what about the composition, size and morphology of these monomers? Did they form within the early Solar System or before? Thirdly, how were the components and the structure of the dust particles processed and altered by the formation and evolution of the nuclei? How did the processes of dust ejection from the nucleus, which remain highly speculative, alter the particles? Has the collection process significantly affected our measurements?

Similarly, links with other cosmic dust particles are already pointed out or need further investigations. While clear similarities appear between cometary dust and CP-IDPs collected in the stratosphere or UCAMMs collected in Antarctica, what about their organics fraction and possible asteroidal sources? To what extent are some outer main-belt primitive asteroids similar to comets, and could future in-situ characterization or sample returns address this issue?

Some of these open questions might be solved in the coming years by further studies from the enormous amount of data that the Rosetta mission has provided. More progress requires sophisticated cross-platform analysis combining the insight of past space missions, elaborate remote observations of comets from Earth and near-Earth based telescopes, interpreted through improved numerical and experimental simulations, and hopefully the development of technological steps allowing sample returns of fragile cometary material in a not too distant future. NASA has preselected in December 2017 two proposals as possible New Frontiers 4 missions, one of them (CAESAR) proposing to return a sample from 67P/C-G; a final selection between the two missions expected in 2019, for a launch sometime in 2025. Meanwhile, some of the above-mentioned open questions should be solved in the coming years by further studies from the enormous amount of data that the Rosetta mission has provided.

Acknowledgements

We would like to warmly acknowledge the ISSI for having organized a Cosmic dust workshop in November 2016, and ESA for making possible the first rendezvous with a comet through the Rosetta mission. ACLR acknowledges support from Centre National d’Etudes Spatiales (CNES) in the realization of instruments devoted to space exploration of comets and in their scientific analysis. H.C. acknowledges support from CNES. C.E. thanks CNES, PNP, DIM-ACAV, Labex P2IO and ANR for support. G.J.F. is supported by NASA Emerging Worlds grant NNX17AE59G. J.L. acknowledges support from CNES. T.M. acknowledges funding by the Austrian Science Fund FWF P 28100-N36. OP acknowledges a postdoctoral research fellowship from CNES. N.T. is supported through Swiss National Science Foundation grant number 20020 – 165684.

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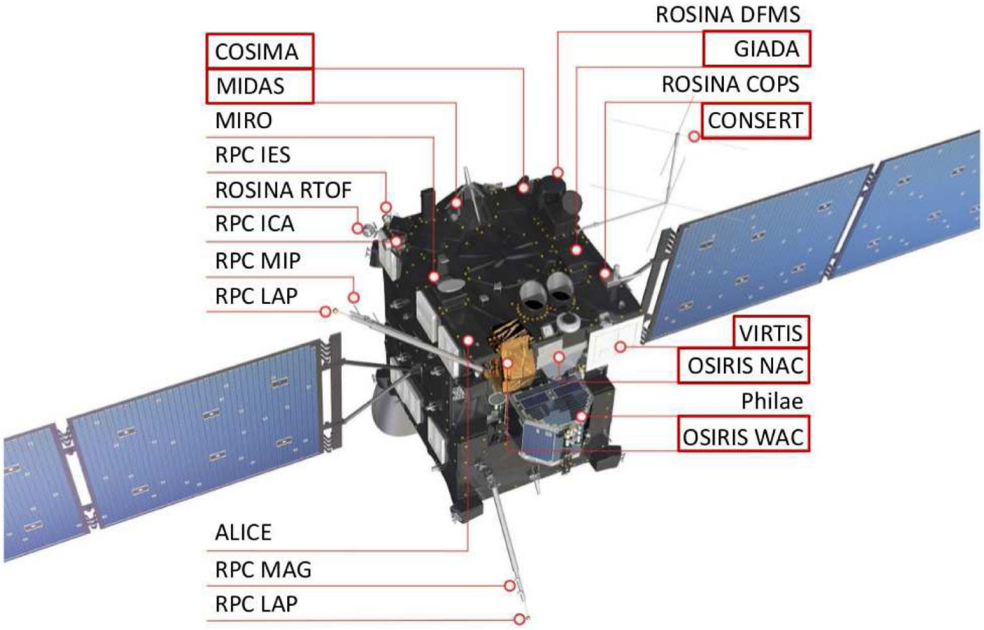

Fig. 1.

Rosetta with labelled instruments, including the lander before its release. The dedicated dust analysing instruments COSIMA, GIADA and MIDAS, as well as the OSIRIS camera system, the VIRTIS VIS/NIR imaging spectrometer and the CONSERT antenna are located on the panel of Rosetta that is mainly oriented towards the cometary nucleus. After ESA/ATG medialab.

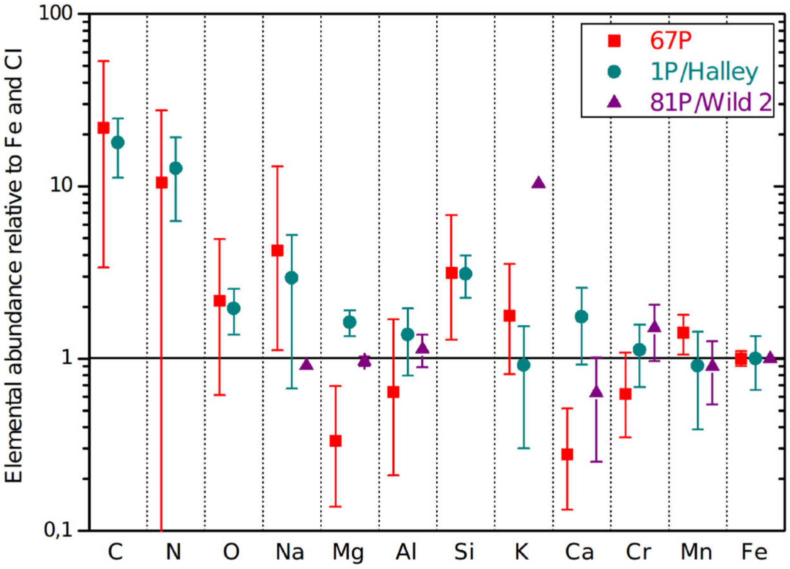

Fig. 2.

Comet 67P/C-G dust elemental ratios relative to Fe and to the CI chondrite composition [Lodders 2010] compared to 1P/Halleys dust and 81P/Wild 2s dust collected in Stardust aerogel. The values correspond to the relative ratios (E/Fe)comet / (E/Fe)CI. The N/C atomic ratio has been measured by Fray et al. (2017). The error bars for 67P/C-G data come from the uncertainties on the determination of Relative Sensitivity Factors (RSFs) uncertainties and can be amplified by successive normalizations. For instance, the uncertainty displayed for C is the addition of uncertainty on the RSF for calculation of C/Si, plus uncertainty for Si/Fe, plus uncertainty on C/Fe in CI-type chondrite. Therefore, error bars can be “artificially” enhanced due to successive normalizations to compare all elements on a same plot (this explains why error bars on N are so large in this plot, compared to the actual value measured for N/C = 0.035 ± 0.011 [Bardyn et al. 2017].

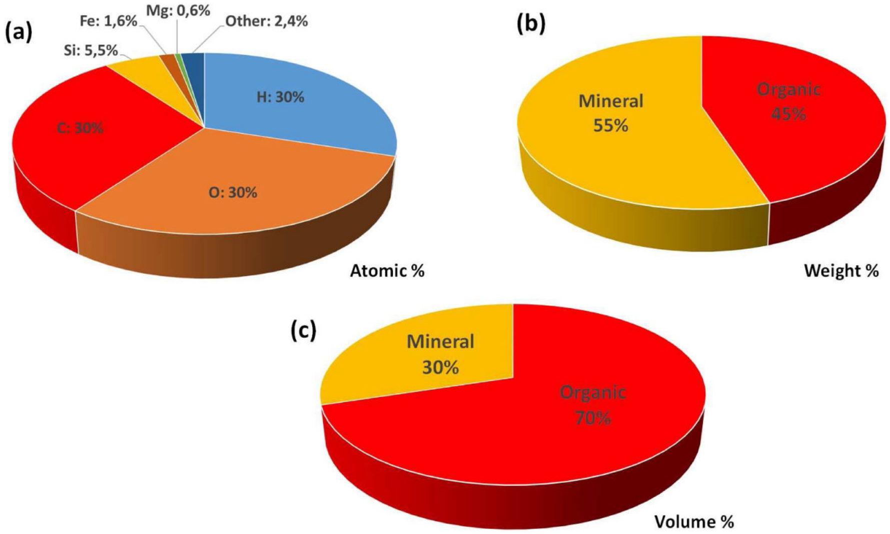

Fig. 3.

Composition of 67P/C-G dust particles. (a) Relative abundance of elements in atom numbers for 67P/C-G dust particles. In this chart, H abundance is not directly measured and the atomic ratio H/C=1 is assumed. Elements under the label “other” include mainly N, Na, Si, and Mn, which relative abundances have been measured with COSIMA, and elements such as S and Ni, not yet quantified with COSIMA, but assumed to have a Solar abundance. (b) Tentative repartition between a mineral and an organic component assuming that elements such as C, N, H and some of the O are the constitutive elements of the organic phase, while the remaining O and other elements are included in the mineral phase. For the oxygen, it is assumed as an upper limit that minerals can be at most with a SiO_4 stoechiometry, the remaining O being incorporated in the organic phase [Bardyn et al. 2017]. (c) Relative abundance in volume of mineral and organic components in 67P/C-G dust particles. This is calculated considering that a relative density for minerals of 3, and a relative density of 1 for organic molecules.

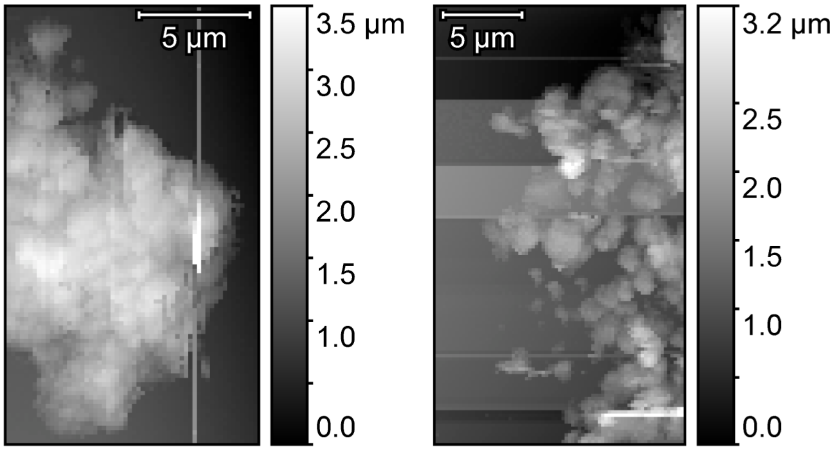

Fig. 4.

Left panel: A typical compact particle collected with MIDAS, extending beyond the field of view and exhibiting a well-defined boundary. The surface features at smaller scales are interpreted as individual units composing the dust. Right panel: A large fluffy particle (also extending beyond the field of view of MIDAS) that is interpreted to represent the remains of a fractal aggregate with fractal dimension $D_f = 1.7 \pm 0.1$ that compacted on collection [Mannel et al. 2016]. Another possibility, the rebound of a larger dust particle bouncing on the target and depositing a surface layer, is less likely due to the structural differences found in experimental tests [Ellerbroek et al. 2017]. ESA/Rosetta/IWF for the MIDAS team IWF/ESA/LATMOS/Universiteit Leiden/Universität Wien

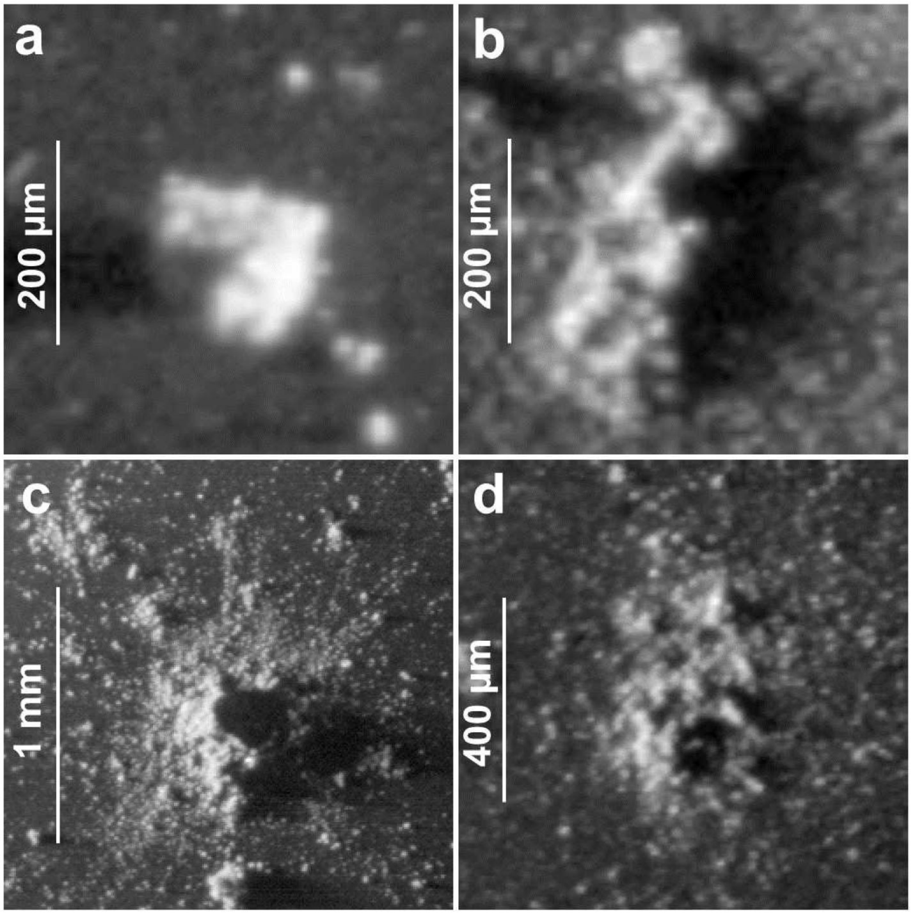

Fig. 5.

Morphology of particles collected by COSIMA, using the classification of Y. Langevin et al., 2016; 5.a: “compact” particle exhibiting well-defined boundary; 5.b “glued cluster”, with sub-components apparently linked together by a matrix.; 5.c “rubble pile”, with a central mound surrounded by an apron of smaller sub-components; 5.d: “shattered cluster”, with widely distributed components and a size to height ratio smaller than 10. Such particles present morphological similarities with the largest particles collected by MIDAS (Fig. 4), which are 10 times smaller.

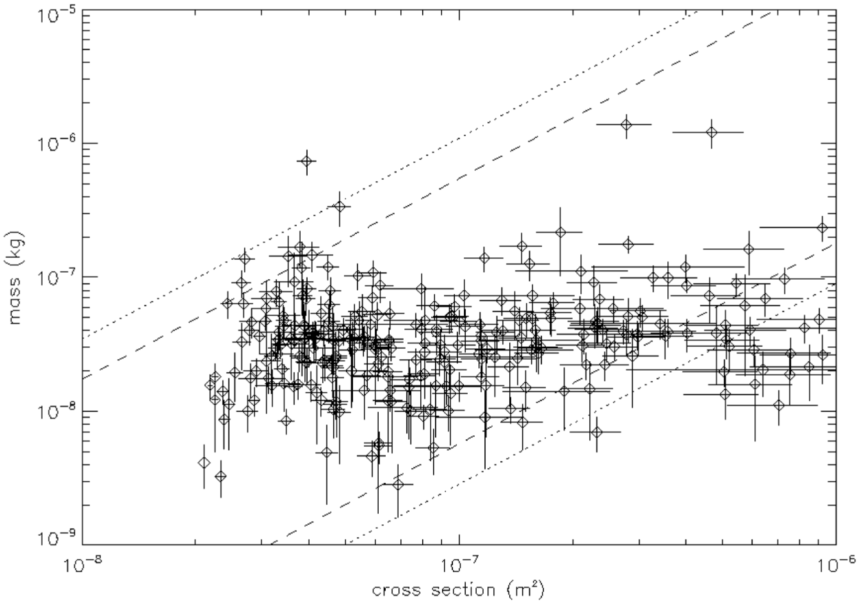

Fig. 6.

Mass and cross-section measurements of compact particles detected by GIADA from August 2014 to September 2016 (the error bars refer to 1σ 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, $\rho_2 = 1200$ kg m^{-3} (lower lines). The GDS signal saturates at a cross section > 10^{-6} m^2. Particles with cross-sections < 2 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 10^{-7} kg was very low during the entire mission due to the spacecraft safety constraints. All these facts explain why all data are distributed in a mostly horizontal cloud. The particles close to the upper dotted and dashed lines have an almost zero porosity, and are compact aggregates of minerals condensed in the inner protoplanetary disc (they are too large to have an interstellar origin [Brownlee 2014]). The particles at right of the lower dotted and dashed lines have both a large porosity and a composition dominated by hydrocarbons. The particles in between are a porous mixture of minerals and hydrocarbons.

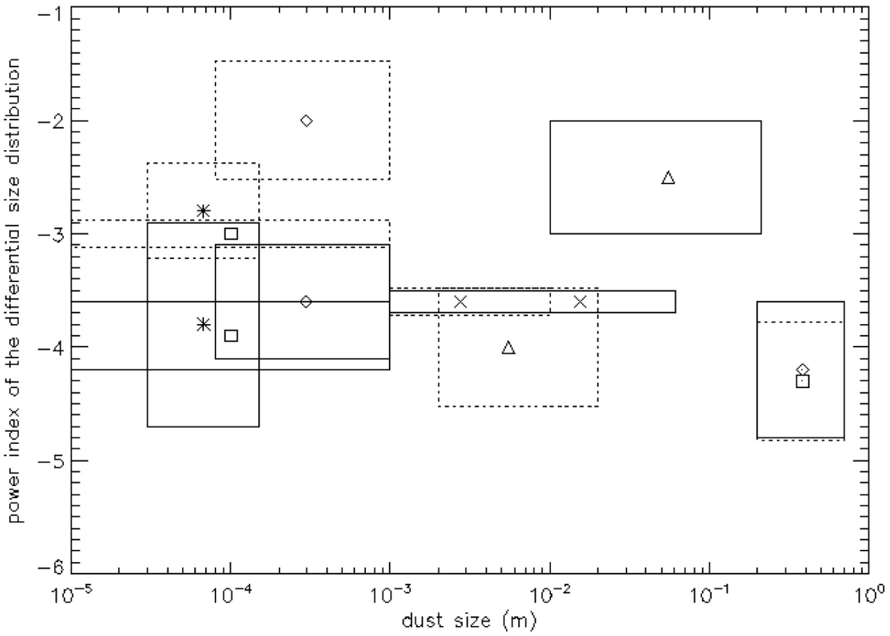

Fig. 7.

Power index of the differential size distribution of 67P/C-G. Dotted lines: power index before the 2015 equinox. Continuous lines: power index after the 2015 equinox, up to just after the 2015 perihelion. The ranges along the *x* axis show the instrument sensitivity, the ranges along the *y* axis are given by the uncertainty of the power index. Stars: COSIMA data [Merouane et al. 2017]. Diamonds: GIADA data [Rotundi et al. 2015] [Fulle et al. 2016c]. Triangles: OSIRIS observations of single particles in the coma [Rotundi et al. 2015] [Fulle et al. 2016c] [Ott et al. 2017]. Dotted diamond: OSIRIS observations of pebbles in Sais [Pajola et al. 2017a]. Dotted square: ROLIS observations of pebbles in Agilkia [Pajola et al. 2017a]. Squares: Ground-based observations, tail models [Moreno et al. 2017]. Crosses: Ground-based observations, trail models [Moreno et al. 2017].

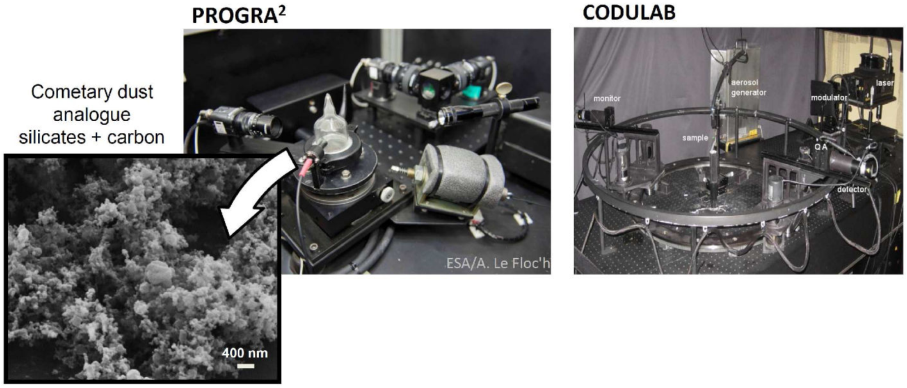

Fig. 8.

Instruments PROGRA^2 [Hadamcik et al. 2009a] and CODULAB [Muñoz et al. 2011], used to measure, through experimental studies in the laboratory or under microgravity conditions, the light scattering properties of various analogues of cometary dust in suspension.

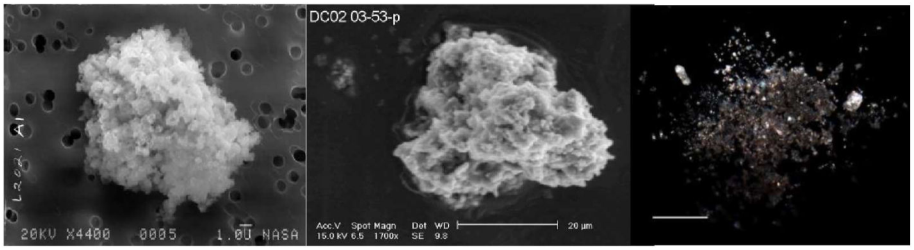

Fig. 9.
From left to right, ordered by increasing sizes: Electron micrograph of stratospheric IDP (Particle L2021A1, about 13 × 10 *μ*m, credit NASA) ; Electron micrograph of Antarctic micrometeorite DC02-03-53 collected near the Concordia station (size about 30 × 40 *μ*m, [Duprat et al. 2007]); Optical image of the giant cluster IDP U2-20GCA (scale bar 100 *μ*m) [Messenger et al. 2015]).

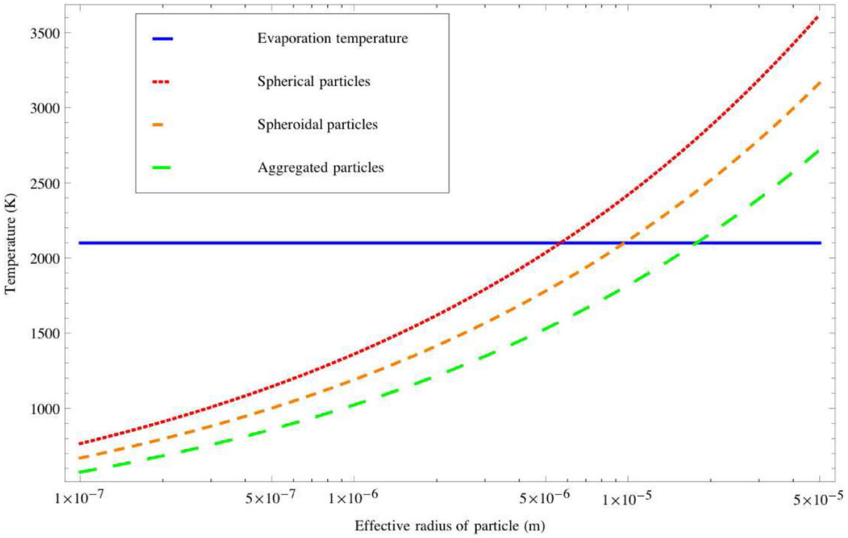

Fig. 10.

Maximum equilibrium temperatures for particles entering the Earth atmosphere at 30 km s^{-1}. The horizontal line corresponds to a typical temperature of sublimation of 2100 K (adapted from [Levasseur-Regourd and Lasue 2011]).