LETTER

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Comet 67P/Churyumov–Gerasimenko sheds dust coat accumulated over the past four years

Rita Schulz[1], Martin Hilchenbach[2], Yves Langevin[3], Jochen Kissel[2], Johan Silen[4], Christelle Briois[5], Cecile Engrand[6], Klaus Hornung[7], Donia Baklouti[3], Anaïs Bardyn[5,8], Hervé Cottin[8], Henning Fischer[2], Nicolas Fray[8], Marie Godard[6], Harry Lehto[9], Léna Le Roy[10], Sihane Merouane[2], François-Régis Orthous-Daunay[11], John Paquette[2], Jouni Rynö[4], Sandra Siljeström[12], Oliver Stenzel[2], Laurent Thirkell[5], Kurt Varmuza[13] & Boris Zaprudin[9]

Comets are composed of dust and frozen gases. The ices are mixed with the refractory material either as an icy conglomerate[1], or as an aggregate of pre-solar grains (grains that existed prior to the formation of the Solar System), mantled by an ice layer[2,3]. The presence of water-ice grains in periodic comets is now well established[4–6]. Modelling of infrared spectra obtained about ten kilometres from the nucleus of comet Hartley 2 suggests that larger dust particles are being physically decoupled from fine-grained water-ice particles that may be aggregates[7], which supports the icy-conglomerate model. It is known that comets build up crusts of dust that are subsequently shed as they approach perihelion[8–10]. Micrometre-sized interplanetary dust particles collected in the Earth's stratosphere and certain micrometeorites are assumed to be of cometary origin[11–13]. Here we report that grains collected from the Jupiter-family comet 67P/Churyumov-Gerasimenko come from a dusty crust that quenches the material outflow activity at the comet surface[14]. The larger grains (exceeding 50 micrometres across) are fluffy (with porosity over 50 per cent), and many shattered when collected on the target plate, suggesting that they are agglomerates of entities in the size range of interplanetary dust particles. Their surfaces are generally rich in sodium, which explains the high sodium abundance in cometary meteoroids[15]. The particles collected to date therefore probably represent parent material of interplanetary dust particles. This argues against comet dust being composed of a silicate core mantled by organic refractory material and then by a mixture of water-dominated ices[2,3]. At its previous recurrence (orbital period 6.5 years), the comet's dust production doubled when it was between 2.7 and 2.5 astronomical units from the Sun[14], indicating that this was when the nucleus shed its mantle. Once the mantle is shed, unprocessed material starts to supply the developing coma, radically changing its dust component, which then also contains icy grains, as detected during encounters with other comets closer to the Sun[4,5].

Since August 2014, the ESA Comet Rendezvous Mission, Rosetta[16,17], has been in orbit around the Jupiter-family comet 67P/Churyumov-Gerasimenko, monitoring the evolution of the comet's nucleus, near-nucleus region, and inner coma as a function of increasing solar flux input, as the comet moves towards the Sun. As part of these studies, the COmetary Secondary Ion Mass Analyser (COSIMA)[18] onboard Rosetta is collecting comet grains from the near-nucleus region and the inner coma onto special target plates[19], which are subsequently imaged and compositionally investigated by time-of-flight secondary ion mass spectrometry using an indium ion source. The grain collection commenced at a heliocentric distance of 3.57 astronomical units (where 1 AU is the average Sun–Earth distance), when the comet was still at low activity. The optical analysis of the grains captured on the target plates at distances beyond 3 AU shows that most have fragmented upon capture and a large fraction of grains more than 50 μm across have shattered. Figure 1a shows a typical example of a dust particle that has crumbled into a rubble pile upon collection, while Fig. 1b shows an example of a dust particle that has shattered into a loosely connected cluster with a wide range of sub-component sizes. These two types of feature are representative of most large particles collected at less than 30 km from the nucleus during the first three months of the orbital phase. Given that the dust particles hit the target with a relatively low velocity ($1–10\ \mathrm{m\ s^{-1}}$)[19], their tensile strength must be very low. From the inertial deceleration forces upon grain capture the strength of the material can be approximated, and a first rough estimate relevant for the present fragmentation process is on the order of 1,000 Pa.

The disintegration of cometary grains in the coma is often described as resulting from an icy grain component that evaporates when exposed to solar radiation, producing a secondary source for comet gaseous material[20,21]. A dusty secondary source can, however, also be attributed to certain organic grains that are not mantled by water ice[22]. The coma dust returned by Stardust[23] featured various types of grain, including specimens that had disintegrated along the deceleration tracks when entering the aerogel (the ultralight porous gel in which the grains were captured) at velocities of the order of $6\ \mathrm{km\ s^{-1}}$, and hence were composed of very fine or thermally unstable components[24,25]. The morphology of the grains collected by COSIMA supports the presence of solely refractory material. A grain composed of an ice–mineral mixture would not shatter at low-velocity collection; instead, the icy part of such a grain would evaporate very shortly after collection, leaving one or more voids in the particle that remains on the target plate. Grains composed of (nearly) pure water-ice would evaporate at or shortly after collection and create a dark signature on the target plate. At the scale of the COSIMA image resolution (pixel size is 14 μm), there is no hint of volatiles having left the grains after collection. In other words, there is no indication of an ice–mineral mixture, or of pure icy grains hitting the target. This is in contrast to cometary grains remotely observed, or collected before the Rosetta mission.

The most important difference between the Stardust and COSIMA grains is the heliocentric distance at which they were captured. The Stardust samples were collected during a comet fly-by at 1.85 AU, whereas the grains collected by COSIMA were dragged off the nucleus of a

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[1]European Space Agency, Scientific Support Office, Keplerlaan 1, Postbus 299, 2200 AG Noordwijk, The Netherlands. [2]Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077 Göttingen, Germany. [3]Institut d'Astrophysique Spatiale, CNRS/Université Paris Sud, Bâtiment 121, 91405 Orsay, France. [4]Finnish Meteorological Institute, Observation services, Erik Palménin aukio 1, FI-00560 Helsinki, Finland. [5]Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (LPC2E), CNRS/Université d'Orléans, 45071 Orléans, France. [6]Centre de Sciences Nucléaires et de Sciences de la Matière, CNRS/IN2P3—Université Paris Sud—UMR8609, Batiment 104, 91405 Orsay campus, France. [7]Universität der Bundeswehr, LRT-7, Werner Heisenberg Weg 39, 85577 Neubiberg, Germany. [8]Laboratoire Interuniversitaire des Systèmes Atmosphériques (LISA), UMR CNRS 7583, Université Paris Est Créteil et Université Paris Diderot, Institut Pierre Simon Laplace, 94000 Créteil, France. [9]University of Turku, Department of Physics and Astronomy, Tuorla Observatory Väisäläntie 20, 21500 Piikkiö, Finland. [10]Center for Space and Habitability (CSH), University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland. [11]Université Grenoble Alpes/CNRS, Institut de Planétologie et d'Astrophysique de Grenoble, 414 Rue de la Piscine, Domaine Universitaire, 38000 Grenoble, France. [12]Department of Chemistry, Materials and Surfaces, SP Technical Research Institute of Sweden, Box 857, 50115 Borås, Sweden. [13]Institut für Statistik und Wahrscheinlichkeitstheorie, Technische Universität Wien, Wiedner Hauptstrasse 7, 1040 Wien, Austria.

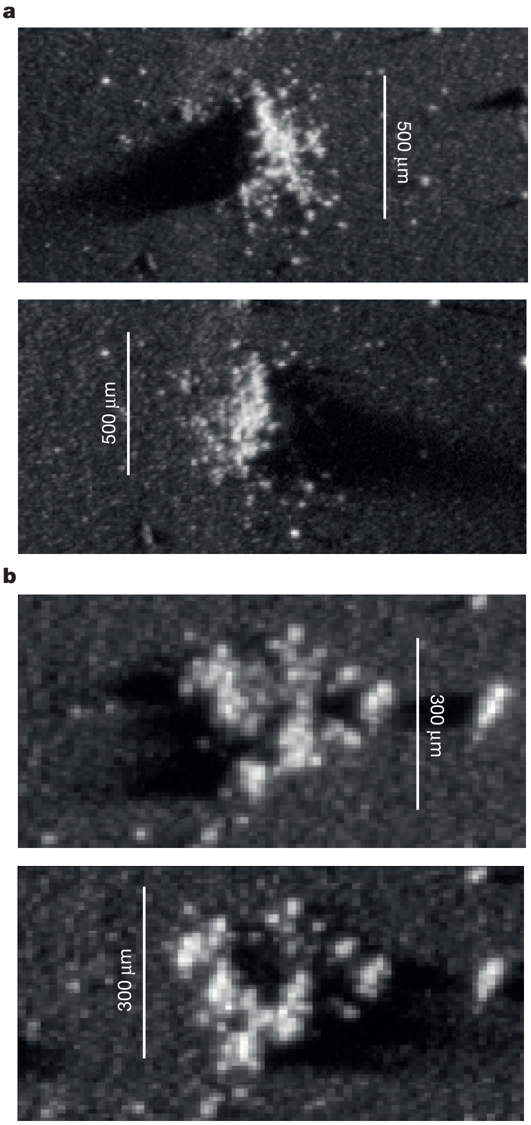

Figure 1 | Dust particles. **a**, An example of a dust particle that crumbled into a rubble pile when collected. The particle was collected at a nucleus distance of 10–20 km, between 25 and 31 October 2014, with corresponding heliocentric distance range 3.11–3.07 AU. The image was obtained with two different grazing illumination conditions (top image illuminated from the right, bottom image from the left). The brightness is presented in logarithmic scale to emphasize the shadows, which indicate that the altitude above the target reaches about 100 µm. As the particle lies 4.2 mm below the centre of the collecting target, the shadows are tilted with regard to the horizontal direction. **b**, An example of a dust particle that shattered when collected. The distance, time of collection, illumination conditions, and logarithmic scale are the same as for **a**. The shadows indicate that the altitude above the target reaches about 60 µm. The two grains visible on the right are not part of the shattered cluster.

re-approaching comet at heliocentric distances greater than 3 AU (as 67P/Churyumov-Gerasimenko returned from its aphelion passage at 5.68 AU having spent about four years at a distance beyond 4 AU). These COSIMA grains therefore come from a dusty layer that has built up over those four years, when the comet was so far from the Sun that the solar radiation was no longer able to create a gas drag that could efficiently remove the dust. The dust therefore remained on the surface, building up an ice-free, fluffy layer, below which lies an ice–dust mixture. When the comet returned to regions of higher solar irradiation the evaporation rate of the volatile gases underneath the dust layer increased again, lifting the particles from the dry upper dust layer into the inner coma, and leaving their original dusty cohabitants (dust frozen together with the gas) behind. This left-behind dust replenishes the existing dusty layer from below, thereby maintaining its thickness in a quasi-steady state until the solar radiation is high enough that the amount of dust removed from the upper layer is larger than the new volatile-free dust produced underneath. As a consequence, the dusty layer will disappear over time and fresh material will come to the surface. The transition may be gradual but could be violent if there is a hard zone under the dusty layer (as may be indicated by the re-bounce of the Philae lander) below which high gas pressures are building up. From the increase in dust production rate observed telescopically in 2008 (ref. 14) we infer that the dusty layer was lost at some stage between 2.7 AU and 2.5 AU. That orbital section will be reached again during the present recurrence of the comet between 24 December 2014 and 20 January 2015, so the loss of the dusty layer has probably already occurred.

The mass spectra of the surface of the COSIMA grains collected beyond 3 AU show a high abundance of sodium. Preliminary values obtained after calibration[26] are as high as 0.8, normalized to $\mathrm{Mg} = 1$. For comparison, the Na abundances ($\mathrm{Mg} = 1$) for comet 81P/Wild-2 are 0.13 (collected in aerogel) and 0.2 (collected on aluminium foil)[27], 0.1 ± 0.06 for comet 1P/Halley[28], and 0.55 for CI chondrites[29]. The Na abundance observed in Perseid and Leonid meteoroids is a factor of 1.5 higher than the chondritic value[15], which fits very well with the value measured by COSIMA. Furthermore, the fluffiness of the COSIMA grains suggests that they would fragment with time after release into the coma. From remote observations, such fragmentation of coma grains has regularly been proposed[30]. Therefore we conclude that the high Na abundance measured by COSIMA, combined with the fluffiness of the grains, supports the hypothesis that these grains represent the parent population of interplanetary dust particles in meteor streams of cometary origin.

Beyond 3 AU, COSIMA has not collected any of the dust that is mixed with sublimating ice, but rather the dust that is present in the upper ice-free dust layer. When the comet loses its fluffy mantle, it is expected that the properties of the grains collected will be very different from those of the grains currently under analysis, which show the properties of 'space-weathered' comet refractory material. The fresh material is likely to be a mixture of ice and dust, and its analysis should provide the detailed structure of this mixture. However, when the comet returns to the outer Solar System, a new dusty mantle will form as the upper layer again becomes free of ice. The formation of such a mantle was considered for re-occurring comets[8] and detailed models exist for short-period comet nuclei[9,10]. The physical processes and timescales of these models are consistent with assumptions made about the nucleus size, orbit and so on for 67P/Churyumov-Gerasimenko. Therefore, the grains collected from this comet provide direct evidence for the existence of its dusty mantle and also an indication of the structure of dust mantles in short-period comets.

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