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Evgenij Zubko, Karri Muinonen, Yuriy Shkuratov, Edith Hadamcik, Anny Chantal Levasseur-Regourd, et al.. Evaluating the carbon depletion found by the Stardust mission in Comet 81P/Wild 2. *Astronomy and Astrophysics - A&A*, 2012, 544, pp.L8. 10.1051/0004-6361/201218981 . hal-00724148

HAL Id: hal-00724148

<https://hal.science/hal-00724148>

Submitted on 17 Apr 2016

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LETTER TO THE EDITOR

Evaluating the carbon depletion found by the Stardust mission in Comet 81P/Wild 2

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Received 7 February 2012 / Accepted 19 July 2012

ABSTRACT

The low abundance of refractory carbonaceous material in samples collected by *Stardust* in comet 81P/Wild 2 coma was completely unexpected. If these results are universal to other comets, this necessitates a reformulation of current models of solar system formation. A polarimetric imaging analysis demonstrates that dust is not uniformly distributed within cometary coma, and that the circumnucleus halo region where the dust samples were collected must contain a low population of carbonaceous particles. Such regions are seen in other comets, suggesting that comet 81P/Wild 2 is not unusual and that the anomalous lack of carbon is not necessarily representative of the entire coma.

Key words. comets: general – comets: individual: 81p/Wild 2 – polarization

1. Introduction

The low abundance of refractory carbonaceous material in samples collected by *Stardust* at its closest approach to the comet 81P/Wild 2 nucleus (about 240 km) was completely unexpected (e.g., Ishii et al. 2008). Carbon is an essential component of organic material, which is thought to be formed in the interstellar medium by processing a solid mixture of carbon, oxygen, nitrogen, and hydrogen with UV radiation and ion bombardment (Jenniskens et al. 1993; Starukhina & Shkuratov 1995). Comets presently observed in the solar system are believed to be remnants of planetesimals that contained organic materials and/or amorphous carbon and are expected to preserve pristine material of the interstellar medium. This theory has long been accepted, and indeed, in situ measurements of comet 1P/Halley carried out by the *VeGa-1* and 2 spacecraft in 1986 confirmed that all analyzed cometary dust particles contain carbonaceous material, and that in 25% of the particles, carbon is the dominant component (Kissel et al. 1986; Fomenkova et al. 1992). Similarly, a high proportion of organic matter was found in all 29 particles analyzed with the Cometary and Interstellar Dust Analyzer (CIDA) mass spectrometer during the comet Wild 2 flyby (Kissel et al. 2004), but most of those particles were analyzed at distances greater than 650 km to the nucleus. Interplanetary dust particles (IDPs) in the Earth's stratosphere (Brownlee et al. 1993; Busemann et al. 2009) also are actively collected. Cometary particles are identified either by their high velocity when entering the Earth's atmosphere (Brownlee et al. 1993) or through dedicated sampling by collecting particles after a close encounter with a comet (Busemann et al. 2009). Dust particles with a cometary origin can also be retrieved from Antarctic snow (Nittler 2010). Cometary dust collected in these ways has a significant carbonaceous component.

The lack of carbonaceous materials in the *Stardust* samples is unlikely to be caused by interaction of the dust particles with aerogel (e.g., Ishii et al. 2008). Analyzing the aerogel samples, Brownlee et al. (2006) observed that components larger than micron-size were often well preserved, whereas smaller or finer-grained components were strongly modified. We would expect a significant population of super-micron carbonaceous particles that would not have been affected by the aerogel. For instance, Fomenkova et al. (1992) observed that about 25% of the comet Halley dust particles consist almost entirely of carbonaceous material and some 50% contain from 10–90% organic material by mass. A high concentration of carbonaceous materials implies that they not only form the outermost layer of the dust particles but are present throughout the dust particle volume. Therefore, if comet Halley is at all representative, this speaks to a very significant percentage of super-micron-sized particles that would not have been affected by the aerogel. Due to the high impact speed ($\sim 19 \text{ km s}^{-1}$) and relatively long interaction with stratosphere, 5- μm cometary IDPs experience heating to 1100–1200 K (e.g., Brownlee et al. 1993). This significantly exceeds the overall heating of the *Stardust* samples, which is just several hundreds degree (Brownlee et al. 2000). As a consequence, carbonaceous materials in the *Stardust* samples should be better preserved compared to the cometary IDPs. Nevertheless, in the former case, their abundance is substantially lower (e.g., Ishii et al. 2008).

The low abundance of refractory carbonaceous materials in 81P/Wild 2 samples is remarkably inconsistent with both the prevalent cometary theory and previous observations. In addition, *Stardust* revealed various refractory minerals formed in the vicinity of the Sun. As a consequence, it was concluded that *81P/Wild 2 more closely resembles an inner solar system*

asteroid than an outer solar system comet with primitive unaltered dust (Ishii et al. 2008). This conclusion is also consistent with the highly cratered surface morphology found in 81P/Wild 2 (e.g. A’Hearn 2006).

The dissonance between our previous knowledge of comets as reservoirs of pristine material and the findings of the *Stardust* mission becomes even more pronounced if we take into account the known history of 81P/Wild 2. Indeed, this comet is a former Kuiper-belt object whose orbit lay between a perihelion at 4.9 AU and aphelion at 25 AU. In 1974, it was diverted into the inner part of the solar system after a close encounter with Jupiter, and currently orbits between 1.6 and 5.2 AU (Ishii et al. 2008). Between 1974 and 2004, the comet experienced only five perihelion passages. Therefore, 81P/Wild 2 was widely expected to be a fresh comet not significantly exposed to solar radiation.

Stardust findings have had an immediate impact on models of solar system formation. It has been suggested, for instance, that the large-scale radial mixing in the solar nebula had been substantially underestimated (e.g., Ishii et al. 2008; Brownlee et al. 2006; Matzel et al. 2010). Alternative resolutions to the *Stardust* challenges are that the samples collected from 81P/Wild 2 are unrepresentative of the entire coma or that this comet is unusual.

2. Spatial variance of degree of linear polarization

Polarimetry is the analysis of the polarization state of light scattered by particles, which provides clues to their properties (e.g. morphology, size, composition), especially when complementary information is available (Hadamcik & Lvasseur-Regourd 2003a; Zubko et al. 2009, 2011a). The most common polarization parameter is the degree of linear polarization $P = (I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$, where I_{\perp} and I_{\parallel} are the intensities of the scattered electromagnetic fields whose electric fields vibrate perpendicular to and within the scattering plane, respectively (see Fig. 1A). Polarization P is dependent on the phase angle α between the direction of illumination and observation, as seen from the dust.

Polarimetric imaging provides evidence that different types of dust are present in different regions within the cometary coma. The three images in Fig. 1B were obtained at small phase angles for comets C/1995 O1 (Hale-Bopp) (left), 81P/Wild 2 (middle), and 22P/Kopff (right) (Hadamcik & Lvasseur-Regourd 2003b). In all cases polarization varies throughout the coma. The polarization maps of these different comets are remarkably similar, suggesting similarity in the dust properties in these regions. For instance, the innermost coma produces a strong negative polarization of up to -6% , which is called the *circumnucleus halo* (Hadamcik & Lvasseur-Regourd 2003b). The material in cometary jets, which is positively polarized, may be superimposed on the image of the halo (e.g. in the C/1995 O1 image of Fig. 1B). The halo is typically a few thousand kilometers across, but the size varies from one comet to another. However, its extent is relatively small, much smaller than the size of the whole coma. When comparing panels in Fig. 1B, one can conclude that the circumnucleus halo of 81P/Wild 2 is similar to those of other comets. Outside the circumnucleus halo, the polarization is much weaker and tends toward positive values.

Figure 1C shows the phase dependence of the degree of linear polarization of the circumnucleus haloes of different comets adapted from Hadamcik & Lvasseur-Regourd (2003b) for comets 81P/Wild 2, C/1995 O1 (Hale-Bopp), C/1990 K1 (Levy), 47P/Ashbrook-Jackson, and 22P/Kopff. The

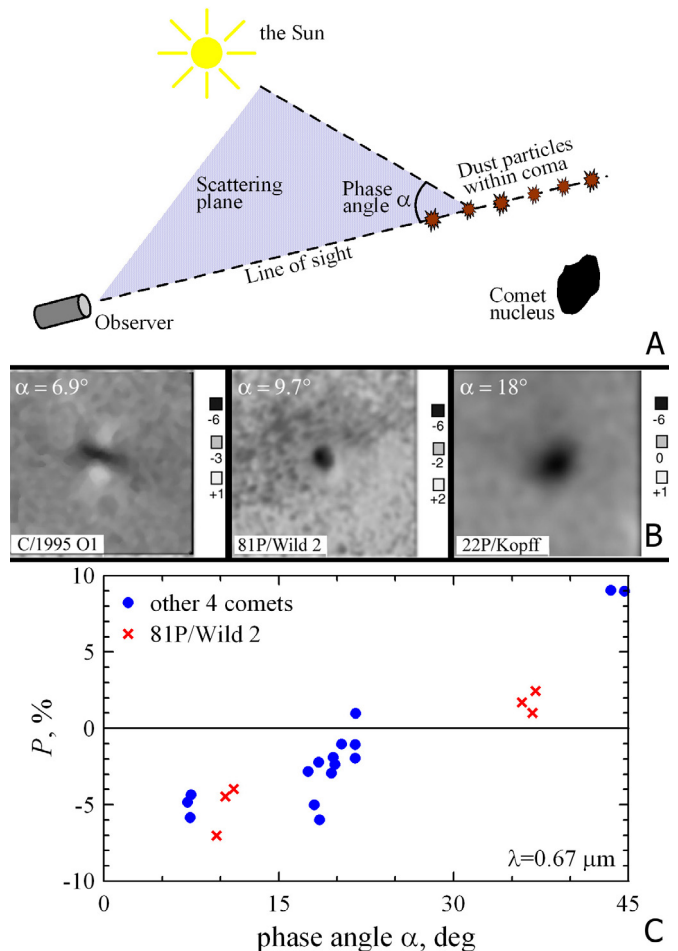


Fig. 1. A) Observation geometry for polarimetric observations of comets. B) Polarimetric images of comets C/1995 O1 (Hale-Bopp) (left), 81P/Wild 2 (middle), and 22P/Kopff (right) obtained at small phase angles. The frame size is equal to 38 000 km, 9000 km, and 4400 km, respectively. C) Synthetic phase dependence of the degree of linear polarization in the circumnucleus halo.

data points corresponding to 81P/Wild 2 (red crosses) are consistent with those for other comets (blue points), and all of them form a branch of negative polarization at small phase angles extending to $\alpha \sim 25\text{--}30^\circ$. This angular profile of the negative polarization is qualitatively similar to that observed in other targets in the solar system (e.g., Johnson et al. 1980; Lvasseur-Regourd et al. 1996; Shkuratov et al. 2011; Zellner & Gradie 1976). An important parameter characterizing the negative polarization branch is the maximum amplitude of the negative polarization. For the circumnucleus haloes, this value $|P_{\min}| \approx 6\%$.

3. Link with chemical composition of dust

Modeling the light scattered by irregularly shaped particles can provide insight into the properties of particles that have particular polarization features. For highly irregular agglomerates, which would be expected in cometary coma, results show that the scattered light is most strongly dependent on the size of the agglomerates and their complex refractive index. Changes in agglomerate morphology have only a minor effect on the scattering properties, so long as it is highly irregular (Zubko et al. 2008, 2011b; Zubko 2012). The high negative polarization in the circumnucleus halo places a strict material constraint on dust particle absorption (Zubko et al. 2009). We demonstrate this

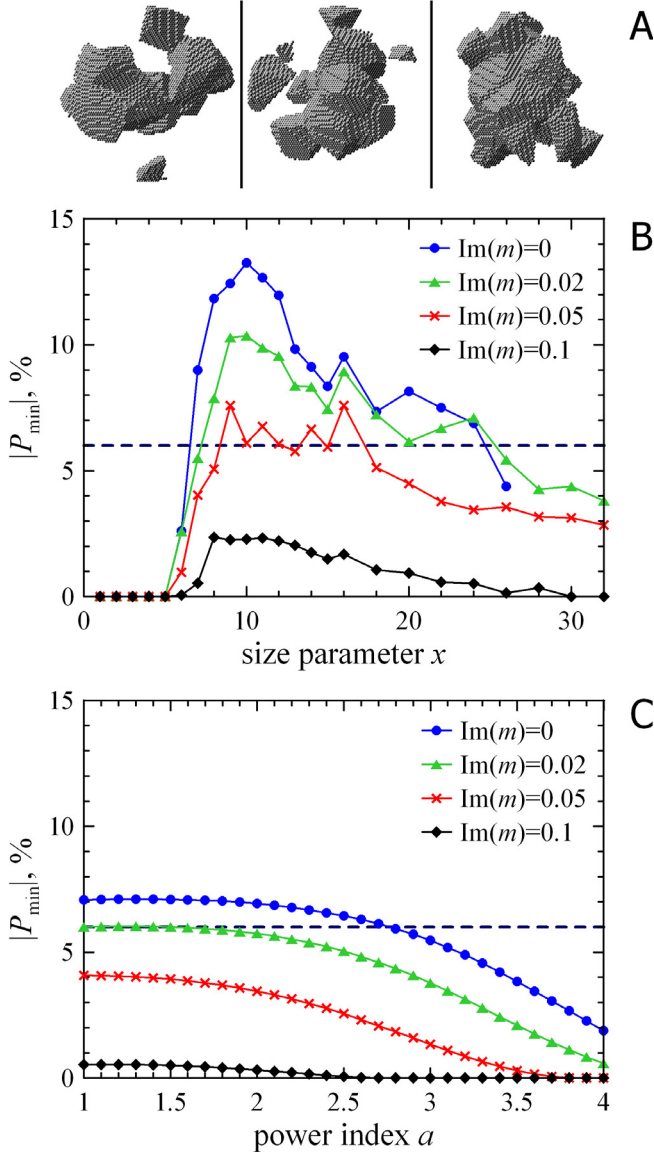


Fig. 2. A) Three samples of agglomerated debris particles. The dependence of the amplitude of minimum polarization $|P_{\min}|$ on B) the size parameter x and C) the power index a of a power-law size distribution for four different refractive indices: $m = 1.5 + 0i$, $m = 1.5 + 0.02i$, $m = 1.5 + 0.05i$, and $m = 1.5 + 0.1i$. The negative polarization of $|P_{\min}| = 6\%$ measured from the circumnucleus haloes is shown by the dashed line.

feature for highly irregular agglomerated debris particles shown in Fig. 2A by generating model particles that satisfy two widely accepted assumptions about cometary dust morphology, that it be highly irregular and fluffy. These agglomerated debris particles explain the unusual spectral behavior of the negative polarization found in comet 17P/Holmes shortly after its explosion in October 2007 (Zubko et al. 2011a). Significant variations of particle packing density ρ from 0.139 to 0.336 have only a minor impact on the negative polarization (Zubko et al. 2011b), and we consider a packing density $\rho = 0.236$ in our calculations. When we consider that the bulk material density for refractory species in comets is in the range 1.5–3.5 g/cm³, the material density in agglomerated debris particles spans the range 0.35–0.83 g/cm³, which is consistent with what was determined from the micro-craters in the aluminum foil that covered the *Stardust* sample collector: 0.3–3 g/cm³ (e.g., Hörz et al. 2006).

A The light scattered from agglomerated debris particles is calculated using the *discrete dipole approximation* (DDA) (e.g., Zubko et al. 2010). Light-scattering properties depend not on particle size but on its ratio to wavelength λ , quantified by the size parameter $x = 2\pi r/\lambda$, where r is the radius of the circumscribing sphere about the particle. Another important characteristic is the complex refractive index m of the particle material, which relates chemical and mineral composition of the given material with its ability to scatter and absorb light.

B Figure 2B demonstrates the dependence of $|P_{\min}|$ on the size parameter x for materials consistent with Mg-rich silicates and organic materials in visible wavelengths (Dorschner et al. 1995; Jenniskens 1993), the two most abundant species within comets (Fomenkova et al. 1992). Mg-rich silicates have little absorption, $\text{Im}(m) \approx 0$. Organic materials have varying absorption depending on the amount of carbon they contain and the processing they have undergone. The shapes of the polarization responses are qualitatively similar in Fig. 2B. The negative polarization does not exist (i.e., $|P_{\min}| = 0$) if the particles are smaller than $x \approx 6$. Then, in the range of $x \approx 6$ –10, the negative polarization appears and rapidly grows with x . An additional increase of x decreases the negative polarization. Material absorption significantly dampens the amplitude of the negative polarization. Indeed, at $\text{Im}(m) = 0$, it exceeds 13%, while at $\text{Im}(m) = 0.1$, it remains substantially less than 3% throughout the range of x . The negative polarization disappears altogether for sufficiently large particles. Because particles with $\text{Im}(m) = 0.1$ cannot produce negative polarization with amplitude greater than 3%, we may immediately conclude that these particles are not the dominant species within the circumnucleus haloes where $|P_{\min}| \approx 6\%$. This conclusion holds throughout the range of the real part of refractive index $\text{Re}(m) = 1.3$ –1.7 (Zubko et al. 2009; Zubko et al. 2011a). Furthermore, it was shown in Zubko et al. (2009) that the negative polarization completely disappears at $\text{Im}(m) = 0.2$ and an additional increase of absorption up to $\text{Im}(m) = 1.3$ does not produce significant negative polarization.

C Real cometary dust is not monodisperse. According to laboratory analyses of micro-craters in the aluminum foil of the *Stardust* spacecraft, for the range of particle sizes from 0.2 to 10 μm , dust obeys a power-law size distribution r^{-a} , where the power index $a = 1.89$ (Price et al. 2010). However, it is important to note that this power index varies for different comets and may also be time-dependent. Figure 2C demonstrates the dependence of $|P_{\min}|$ on the power index a over sizes ranging from 0.2 to approximately 6 μm . The size averaging dramatically suppresses the amplitude of the negative polarization compared to monodisperse particles, since the significant contribution of the small particles does not produce any negative polarization. Since the impact of small particles increases with index a , the negative polarization decreases with increasing a . As a consequence, the constraint on the material absorption becomes significantly stricter when size averaging is included. Particles of any power-law distribution with $\text{Im}(m) > 0.02$ are unable to reproduce the polarimetric properties of circumnucleus haloes. Most carbonaceous materials are highly absorbing. For instance, at $\lambda = 0.7 \mu\text{m}$, organic material in a form expected in the diffuse interstellar medium has a refractive index $m = 1.566 + 0.075i$ (Jenniskens 1993); whereas amorphous and glassy carbon have $m = 2.43 + 0.59i$ and $m = 1.8 + 0.75i$, respectively (Duley 1984). It is clear that none of these materials can appear in any of the observed circumnucleus haloes in significant quantities. Thus, the high negative polarizations measured in the circumnucleus halo of 81P/Wild 2 are consistent with the lack of carbon particles found in the *Stardust* mission.

We emphasize that the circumnucleus halo that produces a strong negative polarization is only a small part of the whole coma. The degree of linear polarization in other parts of the coma is much less negative. Moreover, some features, such as cometary jets, do not reveal any negative polarization at all (Hadamcik & Lvasseur-Regourd 2003b). For instance, in the case of comet 81P/Wild 2 presented in Fig. 1B, the negative polarization in the circumnucleus halo is $P = (-6 \pm 1)\%$; whereas a sunward jet shows positive polarization $P = (+1 \pm 0.5)\%$. Simultaneously, the whole coma of 81P/Wild 2 yields an average $P = (-1.8 \pm 0.5)\%$ (Hadamcik & Lvasseur-Regourd 2003b). One can see that the circumnucleus halo does not dominate the total polarization signal. As a consequence, the lack of carbonaceous materials cannot be attributed to the entire coma region, but only to its innermost part. Indeed, the absence of the negative polarization in cometary jets can be explained as having an abundance of highly absorbing materials (see Fig. 2C). However, as was already noticed, strong material absorption is a distinctive feature of various carbonaceous materials.

Our interpretation of the *Stardust* sampling of the dust particles forming the 81P/Wild 2 circumnucleus halo slightly contradicts the findings in Sekanina et al. (2004), who attributed the discrete burst activity registered by the *Dust Flux Monitor Instrument* (DFMI) (e.g., Tuzzolino et al. 2004) to jets emanating from comet 81P/Wild 2. Non-jet cometary activity (e.g., Belton 2010) is not considered, but the images analyzed in Sekanina et al. (2004) reveal a substantial level of such activity, which appears as numerous non-collimated fluxes originating from the extended surface areas on 81P/Wild 2. It is especially significant that the DFMI sampling of comet 9P/Tempel 1 revealed the same discrete burst activity as in 81P/Wild 2 (e.g., Veverka et al. 2012). However, it is believed that the *Stardust* trajectory did not cross any specific jet in comet 9P/Tempel 1, suggesting that a significant level of heterogeneity is an inherent property of cometary coma, regardless of the presence of jets. These small-scale spatial inhomogeneities (~ 1 km) do not contradict our assumption on the domination in the innermost coma of pre-surface dust particles ejected at low velocity. Other mechanisms can produce coma inhomogeneities, for instance, periodic activity of source(s) of non-accelerated dust particles and/or the impact of radiation pressure (e.g., Fulle 2004). Inhomogeneities in the innermost coma can also result from sublimation of large icy chunks contaminated with refractory cometary species.

4. Conclusions

The circumnucleus halo, as detected by polarization, appears to be a ubiquitous, carbon-depleted (or carbon-hidden) feature of comets because it appears in many of the polarization images obtained at small phase angles. Other regions of the coma display significantly lower negative polarizations that are consistent with the presence of absorbing particles. Cometary jets, for instance, have revealed only positive polarization through all phase angles (Hadamcik & Lvasseur-Regourd 2003b), and 81P/Wild 2 displayed such a sunward jet (Hadamcik & Lvasseur-Regourd 2003b). Since high-carbon content has been a characterizing feature in all samplings prior to the *Stardust* mission, it appears that the anomalous results are due to sampling in this carbon-depleted region. Sampling in this anomalous region may also explain why the crystalline structure of silicates found is different from

the chondritic porous interplanetary dust that was expected to be present (Ishii et al. 2008). While the knowledge of the origin and evolution of comets developed before the *Stardust* mission may not require an immediate revision, the physical mechanisms that produce a circumnucleus halo are currently not well understood. The small size of the halo suggests that it consists of particles that were not accelerated by an expanded gas, like the cometary jets. Its shape may indicate that its dust originated from a relatively large area of the nucleus or that it persists for long periods. Therefore, one can hypothesize that the circumnucleus halo may be caused by near-surface processes directly stimulated by sunlight (e.g., Belton 2010) or through long-term settling of particles within the coma. The preferential selection of non-absorbing particles and the abundance of material resembling chondritic meteorites may provide clues to the halo's origin.

Acknowledgements. This work was partially supported by the Academy of Finland (contract 127461), by the NASA program for Outer Planets Research (grant NNX10AP93G), by the French space agency (CNES) and by the French Programme national de planétologie (PNP). The authors are grateful to the anonymous referee for valuable comments on this paper.

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