LETTER TO THE EDITOR

An update of the correlation between polarimetric and thermal properties of cometary dust

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ABSTRACT

Context. Comets are conglomerates of ice and dust particles, the latter of which encode information on changes in the radiative and thermal environments. Dust displays distinctive scattered and thermal radiation in the visible and mid-infrared (MIR) wavelengths, respectively, based on its inherent characteristics.

Aims. We aim to identify a possible correlation between the properties of scattered and thermal radiation from dust and the principal dust characteristics responsible for this relationship, and therefrom gain insights into comet evolution.

Methods. We use the NASA/PDS archival polarimetric data on cometary dust in the red (0.62–0.73 μm) and K (2.00–2.39 μm) domains to leverage the relative excess of the polarisation degree of a comet to the average trend at the given phase angle (P_{excess}) as a metric of the dust's scattered light characteristics. The flux excess of silicate emissions to the continuum around 10 μm ($F_{\text{Si}}/F_{\text{cont}}$) is adopted from previous studies as a metric of the dust's MIR feature.

Results. The two observables – P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$ – show a positive correlation when P_{excess} is measured in the K domain (Spearman's rank correlation coefficient $\rho = 0.71^{+0.10}_{-0.19}$). No significant correlation was identified in the red domain ($\rho = 0.13^{+0.16}_{-0.15}$). The gas-rich comets have systematically weaker $F_{\text{Si}}/F_{\text{cont}}$ than the dust-rich ones, and yet both groups retain the same overall tendency with different slope values.

Conclusions. The observed positive correlation between the two metrics indicates that composition is a peripheral factor in characterising the dust's polarimetric and silicate emission properties. The systematic difference in $F_{\text{Si}}/F_{\text{cont}}$ for gas-rich versus dust-rich comets would instead correspond to the difference in their dust size distribution. Hence, our results suggest that the current MIR spectral models of cometary dust, which search for a minimum χ^2 fit by considering various dust properties simultaneously, should prioritise the dust size and porosity over the composition. With light scattering being sensitive to different size scales in two wavebands, we expect the K-domain polarimetry to be sensitive to the properties of dust aggregates, such as size and porosity, which might have been influenced by evolutionary processes. On the other hand, the red-domain polarimetry reflects the characteristics of sub-micrometre constituents in the aggregate.

Key words. comets: general – methods: observational – techniques: polarimetric – techniques: spectroscopic

1. Introduction

Comets are among the most pristine leftovers from the nascent Solar System and are conglomerates of ice and dust. The dust properties can reflect the changes that have occurred in the radiative and thermal environment since formation. Observational constraints on these properties will thus bring valuable insights into the evolution of planetesimals in our planetary system.

Dust particles ejected from comets orbiting the Sun mainly reflect sunlight in the visible and near-infrared (NIR) wavelengths (0.5–2.5 μm), yielding a certain degree of linear polarisation (Kiselev et al. 2015). The remaining incident light is absorbed and re-emitted as thermal emission at longer wavelengths, showing particularly distinctive silicate emission features around 10 μm (Hanner & Bradley 2004). The behaviours of both observables are influenced by the intrinsic microphysical

(e.g. size distribution and internal structure) and compositional properties of the dust particles. This leads to the questions of whether these observables are correlated and, if so, which dust properties contribute most to the correlation and what insights do they give us about the evolution of comets.

An earlier systematic study investigating a correlation between the polarimetric and thermal properties in evolutionary perspectives was designed by Kolokolova et al. (2007). The authors demonstrated the following trend: the less amount of time a comet spends in the vicinity of the Sun, the higher its maximum polarisation (P_{max}) in the red domain and the stronger its 10 μm silicate emission feature. However, P_{max} of cometary dust is typically observed at phase angles of $\alpha_{\text{max}} \sim 95^\circ$, and only a handful of comets have been observed at such a high phase angle. Most comets are observed only at $\alpha < 50^\circ$, and their value of P_{max} can only be inferred from extrapolation to α_{max} , with considerable uncertainties. In order to retrieve P_{max} with a maximum of 10% uncertainty, observational data taken up to

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Fig. 1. Polarisation of cometary dust in the K domain as a function of α . The solid curve denotes the average α dependence from Eq. (1). The coloured area covers the 3σ region of the interpolation. The best-fit (minimum χ^2) parameters are $b = 31.17 \pm 0.48\%$, $c_1 = 0.62 \pm 0.05$, $c_2 = (3.41 \pm 0.04) \times 10^{-31}$, and $\alpha_0 = 18^\circ 86 \pm 0^\circ 44$. Diamonds denote points of short-period comets (including Halley types), and circles denote points of long- or non-period comets, respectively.

$\alpha \sim 70^\circ$ are required (Penttilä et al. 2005). For these reasons, we felt the need to study the correlation of the observed parameters with a modified approach. Instead of representing the polarising properties of a given comet's dust by $P_{\max}$, we employ its mean relative deviation from the average trend, P_{excess} , as an indicator.

In Sect. 2 we describe the datasets used in this study, followed by the results and discussion in Sect. 3. In Sect. 4 we present our conclusions.

2. Data description

We retrieved the degree of linear polarisation (P) of cometary dust from the NASA Planetary Data System (PDS): Small Bodies Node archival data (Kiselev et al. 2017). Given ~ 2700 measurements for ~ 70 comets ranging from ~ 0.31 to $2.39 \mu\text{m}$, we considered two spectral regions: the red domain, $0.62\text{--}0.73 \mu\text{m}$, in which the number of data points is the largest; and the K domain of $2.00\text{--}2.39 \mu\text{m}$. From the red domain data, we selected only narrow-band and spectropolarimetric observations to minimise the flux contribution by depolarising gas molecules (e.g. Kwon et al. 2017). In the K domain and at heliocentric distances of $r_H < 0.9$ au, thermal emission contributes a significant (as high as $\sim 30\%$) fraction of the total light received, which could lead to lower observed P than would be received from the scattered light only (Oishi et al. 1978a). For comet C/1975 V1 (West), with observations at r_H ranging from 0.341 to 0.941 au, we used thermally corrected results provided by Oishi et al. (1978a). Except for comet 55P/Tempel-Tuttle and one point of C/1995 O1 (Hale-Bopp), which have r_H of 0.99 au and 0.96 au, respectively, all

Fig. 2. Same as Fig. 1 but in the red domain. The best-fit parameters are $b = 34.85 \pm 0.22\%$, $c_1 = 1.09 \pm 0.02$, $c_2 = 0.46 \pm 0.01$, and $\alpha_0 = 20^\circ 98 \pm 0^\circ 24$.

other observations were made at $r_H > 1$ au; thus, we can rule out the dominance of thermal emission in the polarised signals.

Figures 1 and 2 show the P distribution of the selected comets as a function of the phase angle (α ; the Sun–Comet–Observer angle) in the K and red domains, respectively. We fitted the average phase curve in each domain with the empirical trigonometric function of Lumme & Muinonen (1993):

$$P(\alpha) = b \sin^{c_1}(\alpha) \times \cos^{c_2}\left(\frac{\alpha}{2}\right) \times \sin(\alpha - \alpha_0), \quad (1)$$

where b , c_1 , c_2 , and α_0 are the wavelength-dependent free parameters that shape the curve. We specify the best-fit parameters in the figure captions.

We next divided the observed values of P by the fitted one at the given α . For each comet, we calculated the mean of this ratio, P_{excess} , from all available observations weighted by the square of the errors of the data points to investigate the deviation of its P value from the mean behaviour of comets. We used only data from $\alpha > 30^\circ$ to avoid the influence of an interference effect of internal waves within the dust particles (i.e. the coherent-backscattering effect) that prevails in the negative polarisation branch ($\alpha \lesssim 22^\circ$ for cometary dust; Muinonen et al. 2015). The resultant P_{excess} values are tabulated in Table A.1, with detailed descriptions given in Appendix A.

For comets with available polarimetric information as described above, we compiled the flux ratio of the $10 \mu\text{m}$ silicate emission to the local continuum ($F_{\text{Si}}/F_{\text{cont}}$) from the literature. If for a given comet this ratio had been measured during multiple epochs, we used the weighted-mean $F_{\text{Si}}/F_{\text{cont}}$ of the individual measurements. If no thermal observations had been conducted for a comet at a similar epoch to its polarimetric study, we employed a weighted mean of $F_{\text{Si}}/F_{\text{cont}}$ values taken around the smallest r_H (i.e. likely around the peak of comet activity). We assigned $F_{\text{Si}}/F_{\text{cont}} = 1.00 \pm 0.15$ for comets that showed no

Fig. 3. Interrelations between the P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$ of cometary dust in the K (a) and red (b) domains, respectively, with Spearman's rank correlation coefficient (ρ) shown in the upper left of each panel. The meaning of the symbols is the same as in Figs. 1 and 2. Black circles and squares around the comet symbols indicate carbon-rich and silicate-rich comets, respectively, as defined in the main text.

excess silicate emission. Consequently, 14 and 9 comets in the red and K domains, respectively, were utilised to search for a relationship between the polarimetric and thermal properties of the dust particles. Their characteristics and references are summarised in Table A.1, and the ancillary information of the comets used for the analysis (e.g. the aperture size and the observing epoch) is provided in Appendix A.

3. Results and discussion

Figure 3 shows the interrelation between P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$ of the cometary dust in the K (a) and red (b) domains. Our method to calculate Spearman's rank correlation coefficient (ρ) and its errors is described in Appendix B. In the K domain, we observe a strong positive correlation between the two quantities ($\rho = 0.71^{+0.10}_{-0.19}$), while they appear nearly uncorrelated in the red domain ($\rho = 0.13^{+0.16}_{-0.15}$).

We put open circles and squares around carbon-rich and silicate-rich comets, respectively, to see whether this metric yields a meaningful classification of the comets. We count a comet as carbon rich if its silicate-to-amorphous carbon mass ratio (Si/C) is less than unity. This ratio is typically

estimated by mid-infrared (MIR) spectral modelling (see e.g. Swamy et al. 1988; Wooden et al. 1999). For 67P/Churyumov-Gerasimenko (67P), we used in situ results showing the Si/C ~ 0.2 (Bardyn et al. 2017). There are no Si/C values reported for comets C/2000 WM1 (LINEAR), 10P/Tempel 2, C/1989 X1 (Austin), or C/1996 B2 (Hyakutake).

Despite incomplete information, carbon-rich comets in both domains appear to have systematically weaker silicate emission features than silicate-rich comets. However, P_{excess} values of carbon-rich comets are widely distributed horizontally for both wavebands, showing no difference between silicate-rich and carbon-rich comets in polarisation. We conclude from Fig. 3 that the dust composition would be a peripheral factor in explaining the observed interdependences of P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$. Moreover, supposing that the scattering cross-section of coma dust is dominated by non-Rayleigh particles (Fulle et al. 2000; Kolokolova et al. 2004), we would expect a composition-driven dependence of the two metrics to manifest as an anti-correlation rather than the observed positive correlation. That is because more strongly absorbing (carbon-rich) dust would yield a higher P than transparent dust (Zubko et al. 2014, 2016) and would suppress silicate features by enhancing the underlying featureless pseudo-continuum signal (see e.g. Wooden 2002).

These two considerations lead us to dismiss dust composition as the main parameter behind the $P_{\text{excess}} - F_{\text{Si}}/F_{\text{cont}}$ correlation. Instead, we consider the dust size to be a main controlling factor. Small particles in the Mie scattering regime (of order 0.1–1 μm in the NIR) are hotter and show a more robust contrast of 10 μm silicate emission over the continuum than larger particles (Lisse et al. 2004; Sitko et al. 2004). Such small particles also show higher P than larger ones (Kimura et al. 2006); thus, dust size can explain the observed positive correlation of the parameters.

To further explore this hypothesis, we divided the comets into ‘gas-rich’ and ‘dust-rich’ groups and searched for their distribution in the same two-dimensional parameter space as used in Fig. 3. The criterion for classification is either (i) the W values (the flux ratio of C_2 emission bands at 5140 $\text{\AA}$ to the local continuum at 4845 $\text{\AA}$), or any similar gas-to-continuum-flux ratio estimates, where dust-rich and gas-rich comets typically show $W < 500$ and $W > 1000$, respectively (Swamy 2010); or (ii) if there is no available W value, the aperture dependence of P in broadband filters. The latter criterion is based on Fig. 1 in Kolokolova et al. (2007), which suggests that in gas-rich comets (according to criterion (i)) the average P across the coma steeply decreases with aperture size, while in dust-rich comets the aperture dependence of P is weak. We consider comets with unmeasured W but that show a steep decrease in the average P ($\gtrsim 30\%$) as the radial distance increases out to the order of 10^4 km to be gas rich.

Figure 4 shows the resultant distribution of the two groups in both spectral domains. In K band, although the gas-rich comets are located below the dust-rich comets, within each group we find a strong positive correlation between P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$. The correlation coefficient is comparable for both groups ($\rho \sim 0.80$) and is stronger than for the dataset as a whole in Fig. 3. Additionally, in the red domain the gas-rich comets are on average located lower than the dust-rich comets, but no discernible correlation of the two parameters is shown.

In the following, we aim to gain insight into which dust property is the main driver of the correlation in K band observed in Figs. 3 and 4. As mentioned above, gas-rich comets observed at 0.5–0.9 μm share the characteristic of frequently showing a steep decrease in the observed average P over the outer coma,

along with an increase in the flux ratio of gas molecules to the total signal. This contrasts with the behaviour of dust-rich comets, which show an almost constant radial P dependence within $<10\%$ (Kolokolova et al. 2007). When P is measured in broadband filters with the spatial resolution of thousands of kilometres, which is typical for ground-based telescopes, it thus tends to be lower in gas-rich comets than in dust-rich comets. However, if measured in narrow-band filters or with spectropolarimetry, the gas-rich comets also show their intrinsic dust P values because depolarised light in emission lines is excluded from the measurement. The resulting aperture-averaged P is not as low as observed in broadband and is nearly constant across the coma (Jockers et al. 2005; Kwon et al. 2017, 2018).

Kolokolova et al. (2007) suggested that such an aperture-size dependence of P could be related to the radial distribution of the coma dust, which in turn could reflect the dust porosity. In this interpretation, gas-rich comets have relatively heavy, compact dust particles lingering around the nucleus and thus show higher gas contamination in the wide aperture broadband polarimetric data. In contrast, the more porous dust in dust-rich comets has a larger cross-section-to-mass ratio that reaches farther in cometocentric distance under the same condition, yielding more or less constant P radial variations. For Fig. 4, this would mean that the green symbols refer to comets with predominantly ‘compact’ dust, while red symbols indicate more ‘porous’ dust. This interpretation is also consonant with the dust modelling results that show that highly ‘fluffy’ particles (Ballistic Cluster-Cluster Aggregate; BCCA) can retain strong silicate emission features, even for $100\text{ }\mu\text{m}$ -sized dust, while more compact ones (Ballistic Particle-Cluster Aggregate; BPCA) show featureless MIR spectra (Kimura et al. 2009)¹. Furthermore, given some overlap between the ‘carbon-rich’ (Fig. 3) and gas-rich (Fig. 4) comets, compact dust in the gas-rich comets might produce weaker silicate features that could be attributed to smaller Si/C ratios and hence lead to the comets being classified as carbon-rich. Hence, both the distinction between gas-rich and dust-rich comets and that between carbon-rich and ‘silicate-rich’ comets could in truth be the distinction between porous and compact dust.

In situ European Space Agency/Rosetta observations have revealed the hierarchical nature of the dust of comet 67P from metre-scale boulders down to the sub-micrometre monomers (Bentley et al. 2016). Observations in 67P’s innermost coma showed that the ejected dust is barely present as individual grains, being bound in aggregates (or agglomerates), which can be classified by different mechanical strengths depending on their bulk porosity (Fulle et al. 2016; Güttler et al. 2019). The number density of fluffy and compact particles varies with 67P’s season (Longobardo et al. 2020): Dust ejected from more evolved, smooth terrains shows lower porosity, whereas dust from fresh, rough terrains shows higher porosity. Hence, porosity may be indicative of the degree of processing experienced by the dust, which is also in line with the conclusions of Kolokolova et al. (2007).

Fluffy dust particles with a tensile strength of $<10^5\text{ N m}^{-2}$ (Mendis 1991) and a high charge-to-mass ratio (Fulle et al. 2015) are more vulnerable to disintegration due to electro-

¹ Chornaya et al. (2020) recently suggested that even half-millimetre-sized compact olivine particles show the $10\text{ }\mu\text{m}$ silicate features. However, the facts that (i) Chornaya et al. (2020) measure the reststrahlen-band features in reflectance spectra (Sect. 9 in Bohren & Huffman 1983), not emission features in thermal spectra, and (ii) such large, transparent particles cannot explain the observed temperature of cometary dust (e.g. Wooden 2002; Hanner & Bradley 2004) make it hard to directly compare their results to this study.

Fig. 4. Same as Fig. 4 but comets are classified as dust rich (red) and gas rich (green) in the K (a) and red (b) domains, respectively, with ρ values provided in the upper left for each group. The classification criteria are given in the text. Open circles denote points of short-period comets (including Halley types), and filled circles denote points of long- or non-period comets, respectively.

static fragmentation, ice sublimation, and/or radiative torques (Herranen 2020) than low porosity dust. In the end, the high ratio of fluffy versus compact dust particles naturally leads to an increase in the small ($\lesssim$ micrometre-sized) particles in the size distribution of the coma dust as it moves out from the nucleus. This results in a higher P_{excess} and a higher $F_{\text{Si}}/F_{\text{cont}}$ for observations with a thousand-kilometre-sized aperture. Consequently, the dust size, related to the porosity of dust aggregates, would be the determinant in making the two parameters positively correlated. The strong correlation in the K domain would demonstrate that different comets have different average dust porosities, which might be an evolutionary outcome of compact particles being more strongly processed.

This leads to the question of why such $P_{\text{excess}}-F_{\text{Si}}/F_{\text{cont}}$ correlations are absent from the red domain. This might be explained by the different scattering scales. At a wavelength of $\sim 0.6\text{ }\mu\text{m}$, monomers in aggregates have more or less similar dimensions relative to the incident wavelet (Güttler et al. 2019), such that their individual characteristics define the scattering to a large extent. In contrast, the single wavelet of $\sim 2.2\text{ }\mu\text{m}$ can cover multiple monomers, enhancing mutual electromagnetic interaction ($\propto d^{-3}$, where d is the distance between two neighbouring

dipole-like monomers; Jackson 1962), which makes observations more pertinent to how dust is organised in aggregates (i.e. bulk effects; Kolokolova & Kimura 2010; Kwon et al. 2019). The apparent lack of a correlation in the red domain might thus tell us that the monomers' inherent characteristics are independent of porosity. Panel b of Fig. 4 also shows that P_{excess} is not correlated with the dynamic group of the comets. Such a broad similarity of monomer traits between different dynamic groups might further support the idea that short- and long-period comets have similar origins, as suggested by recent dynamical studies (Morbideilli & Rickman 2015).

We should emphasise that it is premature to make statistically significant conclusions from this study due to the small datasets. The outliers in the red domain, particularly 67P and 2P/Encke (purple and navy diamonds, respectively, in Fig. 3), also have no corresponding K-domain polarimetric data, making it challenging to assess whether the observed trend in the K domain is unbiased. Further coordinated studies of polarimetry and MIR spectroscopy are needed to draw a more comprehensive conclusion.

4. Conclusions

We present a new analysis, searching for a possible correlation between the polarimetric and thermal silicate emission properties of cometary dust. We estimated the relative excess of comets' polarisation statuses about the average trend at a given phase angle, parameterised as P_{excess} . The $10\ \mu\text{m}$ silicate emission excess over the continuum $F_{\text{Si}}/F_{\text{cont}}$ was then used to examine the relationship with P_{excess} .

The K domain P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$ are positively correlated for the comets as a whole as well as for gas-rich and dust-rich comets individually. This allows us to claim that (i) the dust composition is secondary in interpreting the correlated observations; and (ii) the dust size and porosity are key factors instead.

We propose that the current classifications of 'gas rich' versus 'dust rich' on the one hand and 'carbon rich' versus 'Si rich' on the other might in reality both be related to the difference between 'low porosity' and 'high porosity', especially as the two classification schemes have considerable overlap in our dataset. With Rosetta results indicating that less porous dust might be more strongly processed, we suggest that the porosity inferred from $F_{\text{Si}}/F_{\text{cont}}$ might help to diagnose the compaction of a comet's dust as a consequence of comet evolution.

In contrast, the red domain P_{excess} seems uncorrelated with $F_{\text{Si}}/F_{\text{cont}}$. Accordingly, we conclude that optical polarimetry is mainly sensitive to the properties of monomers inside an aggregate, while the NIR polarimetry is useful for diagnosing the porosity of the dust aggregates. The distributions in the red domain might further imply that there is a broad similarity between monomers and hence of origins between short-period and non- or long-period comets.

Our results also suggest that the current MIR spectral models of cometary dust, which search for a best fit by simultaneously considering various dust properties (e.g. the size distribution, composition, and porosity; Wooden et al. 2004; Harker et al. 2018; Woodward et al. 2021), should prioritise structural parameters over the composition. We recommend coordinated studies in polarimetry and MIR spectroscopy in order to shed further light on the processes shaping cometary dust particles in our planetary system.

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Appendix A: Ancillary information for the comets used for analysis

The polarimetric and MIR observations for most of the comets were made during approximately the same periods. If a comet was observed in multiple epochs and the period span of its polarimetric observations overlaps the span of its MIR observations, we considered all the overlapped data points. For five comets – C/2013 US10 (Catalina), 19P/Borrelly, 55P/Tempel-Tuttle, C/1990 K1 (Levy), and 2P/Encke – we found no common periods between polarimetric and MIR observations. However, based on the following reasons, we expect two observing modes to observe nearly similar comet environments. For C/2013 US10 (Catalina), both observations were made post-perihelion, and the heliocentric distance (Δr_H) is ~ 0.27 au. The MIR observations for 19P/Borrelly were made one apparition before the polarimetric observations, but at the same r_H . The MIR observations of 55P/Tempel-Tuttle were conducted nine days before the polarimetric observations, but the Δr_H is less than 0.03 au. The MIR observations of C/2001 Q4 (NEAT) were conducted one week before the polarimetric observations, but the Δr_H is less than 0.007 au. The polarimetric observations of 2P/Encke were made pre-perihelion, while its MIR observations were made at post-perihelion, with the $\Delta r_H \sim 0.16$ au. Nonetheless, since 2P/Encke consistently showed no silicate emission features over the local continuum throughout the MIR observations (Gehrz et al. 1989), the usage of $F_{Si}/F_{cont} = 1$ would not be problematic. Although it turns out that the intensity of the silicate emission of a comet can vary within a period of a few days (e.g. Mason et al. 2001), we expect that the usage of the weighted mean of multiple data points taken at similar epochs of the two observing modes would represent a comet's general behaviour relative to the average trend of other comets.

The difference in the aperture sizes applied to the polarimetric and MIR observations was also examined. Most of the comets were sampled with a similar aperture size in the two observing modes, except for five of the comets – C/2001 WM1 (LINEAR), 55P/Tempel-Tuttle, C/1990 K1 (Levy), 21P/Giacobini-Zinner, and 9P/Tempel 1 – which had different aperture sizes (but the sizes were of the same order). The first four comets were observed in two observing modes with aperture sizes ranging from a few thousand kilometres to a few tens of thousands of kilometres at $r_H \gtrsim 1$ au. Their data points thus represent the dust properties in the dust tail coma region, free from any significant collisions or ice sublimations (Marschall et al. 2020). Together with the results of Bonev et al. (2008), which showed that the dust radial profile reaches an equilibrium at ~ 1000 km from the nucleus at $r_H \sim 1$ au, the aperture differences of such an order might sample more or less similar coma dust. For comet 9P/Tempel 1 right after the Deep Impact experiment, on the other hand, both polarimetric and MIR observations applied aperture sizes of less than 1000 km at $r_H \sim 1.5$ au. Since both MIR and polarimetric observations detected impact-induced changes almost simultaneously (e.g. Furusho et al. 2007; Harrington et al. 2007; Harker et al. 2005, 2007; Küppers et al. 2005), we expect that the coma dust properties observed by the two observing modes would not be significantly different. The only comet that has an irreconcilable difference in aperture sizes is C/2001 Q4 (NEAT). Its polarimetric data cover a cometocentric distance of ~ 7100 to 20 000 km, while the MIR data were extracted ~ 760 km from the centre. Although the usage of the weighted mean of its multiple data points places the comet around the centre in the P_{excess} and

Fig. A.1. P_{excess} of comets in the K and red domains as a function of α . The $P_{excess} = 1$ line indicates the interpolated average α dependence derived from Eq. (1).

F_{Si}/F_{cont} plane (pink circle in Fig. 3b) – consistent with the previous study, which showed its silicate spectrum to be similar to those of other long-period comets (Wooden et al. 2004) – the interpretation of this comet's data points should be made with caution due to the systematic difference of the covered coma scale.

Despite the limitations mentioned above, we expect that the usage of the weighted mean of the multi-epoch data points across the wide range of the phase angles could mitigate the systematic differences for some comets and enable us to examine the physical and/or compositional status of a comet relative to the majority of comets. The observed P values in Figs. 1 and 2 are divided by the best-fit average at the given α , as shown in Fig. A.1. The symbols are identical to those in Figs. 1 and 2. Since a single comet taken at different α frequently shows fluctuations in P values around the average trend line, we took a weighted mean for each comet, parameterised as P_{excess} , to address the general polarimetric status of a comet with regard to the majority of comets:

$$P_{excess} = \frac{\sum_{i=1}^n w_i P_{excess,i}}{w_i}, \quad (\text{A.1})$$

where n is the number of P data points at $\alpha > 30^\circ$ for a single comet, $P_{excess,i}$ is the P_{excess} of the i th point of the comet,

Table A.1. Observational characteristics of comets used in Figs. 3 and 4 and their references.

Comet name	Domain	P_r/P_{avg}	$F_{\text{Si}}/F_{\text{cont}}$	Obs. type	C. abundance	Dyn. type	Reference
C/1995 O1 (Hale-Bopp)	Red K	1.673 ± 0.018 1.200 ± 0.082	2.690 ± 0.100	Dust-rich	Low	LPC	(1), (2), (3)
C/2013 US10 (Catalina)	Red K	0.880 ± 0.142 1.005 ± 0.058	1.128 ± 0.100	Gas-rich	High	NPC	(4), (5)
C/2000 WM1 (LINEAR)	Red K	1.116 ± 0.090 1.024 ± 0.063	1.500 ± 0.050	Dust-rich	–	NPC	(6), (7)
1P/Halley	Red K	1.003 ± 0.038 1.040 ± 0.062	1.770 ± 0.190	Dust-rich	Low	HTC	(8), (9), (10)
103P/Hartley 2	Red K	1.018 ± 0.036 0.953 ± 0.053	1.163 ± 0.030	Gas-rich	High	JFC	(11), (12)
10P/Tempel 2	K	0.761 ± 0.079	1.000 ± 0.150	Gas-rich	–	JFC	(13), (14), (15)
19P/Borrelly	K	1.170 ± 0.032	1.250 ± 0.125	Gas-rich	High	JFC	(16), (17)
55P/Tempel-Tuttle	K	0.824 ± 0.026	1.070 ± 0.020	Gas-rich	High	HTC	(18), (19)
C/1975 V1 (West)	K	0.984 ± 0.023	1.420 ± 0.080	Dust-rich	Low	NPC	(20), (21)
C/1987 P1 (Bradfield)	Red	1.105 ± 0.033	1.700 ± 0.200	Dust-rich	Low	LPC	(9), (22), (23)
C/1989 X1 (Austin)	Red	1.002 ± 0.165	1.130 ± 0.020	Gas-rich	–	HTC	(19), (24)
C/1990 K1 (Levy)	Red	1.003 ± 0.065	1.720 ± 0.040	Dust-rich	Low	NPC	(9), (25), (26)
C/1996 B2 (Hyakutake)	Red	1.010 ± 0.015	1.880 ± 0.150	Dust-rich	–	LPC	(27), (28)
C/2001 Q4 (NEAT)	Red	0.975 ± 0.035	1.800 ± 0.200	Dust-rich	Low	NPC	(29), (30)
2P/Encke	Red	1.370 ± 0.169	1.000 ± 0.150	Gas-rich	High	JFC	(31), (32)
9P/Tempel 1 ^(†)	Red	1.066 ± 0.003	1.600 ± 0.150	Dust-rich	High	JFC	(33), (34), (35)
21P/Giacobini-Zinner	Red	0.792 ± 0.035	1.100 ± 0.110	Dust-rich	High	JFC	(9), (36), (37)
67P/Churyumov-Gerasimenko	Red	1.223 ± 0.149	1.000 ± 0.150	Dust-rich	High	JFC	(38), (39)

Notes. Top headers: P_r/P_{avg} , the relative excess of the polarisation degree with regard to the average value at the given phase angle (α); $F_{\text{Si}}/F_{\text{cont}}$, the relative excess of the 10 μm silicate emission feature to the local continuum. LPC, NPC, HTC, and JFC are the abbreviations of long-period comets, non-period comets, Halley-type comets, and Jupiter-family comets, respectively. ^(†)Right after the Deep Impact experiment.

References. (1) Mason et al. (2001); (2) Harker et al. (2002); (3) Kiselev & Velichko (1997); (4) Kwon et al. (2017); (5) Woodward et al. (2021); (6) Joshi et al. (2003); (7) Kelley et al. (2004); (8) Hanner et al. (1987); (9) Chernova et al. (1993); (10) Wooden (2002); (11) Lara et al. (2011); (12) Harker et al. (2018); (13) Tokunaga et al. (1992); (14) Lynch et al. (1995); (15) Paganini et al. (2012); (16) Hanner et al. (1996); (17) Szabó et al. (2002); (18) Watanabe et al. (2001); (19) Sitko et al. (2004); (20) Oishi et al. (1978a); (21) Oishi et al. (1978b); (22) Hanner et al. (1990); (23) Colangeli et al. (1996); (24) Joshi et al. (1992); (25) Lynch et al. (1992); (26) Lisse et al. (1998); (27) Kiselev & Velichko (1998); (28) Mason et al. (1998); (29) Wooden et al. (2004); (30) Ganesh et al. (2009); (31) Gehrz et al. (1989); (32) Kwon et al. (2018); (33) Harker et al. (2005); (34) Küppers et al. (2005); (35) Harker et al. (2007); (36) Hanner et al. (1992); (37) Ootsubo et al. (2020); (38) Hanner et al. (1985); and (39) Bardyn et al. (2017).

and w_i is the weight of the i th point of the comet; this weight is $1/\sqrt{\sum_{i=1}^n (\sigma P_{\text{excess},i})^2}$, where $\sigma P_{\text{excess},i}$ is the error on $P_{\text{excess},i}$. The error on P_{excess} is the standard deviation of $P_{\text{excess},i}$ divided by $\sqrt{n}$. Likewise, the weighted mean of $F_{\text{Si}}/F_{\text{cont}}$ (when multiple epochs are considered for a comet) was retrieved under the same scheme with Eq. (A.1) but was instead weighted by $1/\sqrt{\sum_{i=1}^n (\sigma(F_{\text{Si}}/F_{\text{cont}})_i)^2}$, where $\sigma(F_{\text{Si}}/F_{\text{cont}})_i$ is the error on $F_{\text{Si}}/F_{\text{cont}}$ adopted from the references. For comets that show no excess of the 10 μm silicate feature (comets 10P/Tempel 2, 2P/Encke, and 67P), we found no available information about the signal-to-noise ratios of the spectra nor about the uncertainties of the fitting models of the local continuum, except for the 10–15% uncertainty in the temperature correction used for the underlying continuum fitting of 10P/Tempel 2 (Tokunaga et al. 1992). Hence, we assigned 15% error bars for the comets that have no silicate emission features.

Table A.1 summarises the description of the datasets used for drawing Figs. 3 and 4. Numbers in the last column show references for the $F_{\text{Si}}/F_{\text{cont}}$, the carbon abundance, and the criteria for the classifications of gas-rich versus dust-rich comets. Polarimetric data are quoted from the NASA PDS database (Kiselev et al. 2017) and the subsequent studies of Kwon et al. (2017, 2018, 2019).

Appendix B: Statistical aspects

In order to check for correlations between the two metrics we defined in Sect. 2 and the trends therein, we retrieved the Spearman’s rank correlation coefficient, ρ . Since the Spearman test does not provide the error bar on the coefficient, we carried out Monte Carlo simulation to derive more reliable ρ values. We first generated clones of data points randomly distributed in the Gaussian distribution, the standard deviation of which corresponds to the error bars of the two metrics (i.e. the errors of the weighted-mean P_{excess} and $F_{\text{Si}}/F_{\text{cont}}$ values in Appendix A). Monte Carlo simulation then retrieved the most probable ρ values by sampling 1000 synthetic datasets of $(P_{\text{excess}}, F_{\text{Si}}/F_{\text{cont}})$, yielding a distribution of ρ with a finite width. The resultant ρ distributions are non-Gaussian, such that we adopted the median of the Monte Carlo results as the nominal value and the 68.2% (1-sigma) interval around the median value as the error bars, as in Santos-Sanz et al. (2012). Figures B.1 and B.2 show the distribution of clones and the ρ distribution from the Monte Carlo simulation for the comets in panels a and b in Fig. 3, respectively. The nominal ρ value, its error bars, and the mode value are provided in the caption of the figures. The results for the dust-rich and gas-rich comets in the K domain are shown in Figs. B.3 and B.4, while those in the red domain are shown in Figs. B.5 and B.6.

Fig. B.1. Number distribution of clones randomly generated in the Gaussian distribution whose standard deviation corresponds to the error bars of the two parameters of all comets in the K domain in Fig. 3a (a) and the histogram of the resultant Spearman's rank correlation coefficient ρ of 1000 new samples retrieved from Monte Carlo simulations. *Panel a:* colours do not correspond with those in Fig. 3. *Panel b:* the median of the distribution function with the 68.2% interval around the median value is $0.71^{+0.10}_{-0.19}$, and its mode is 0.76.

Fig. B.2. Same as Fig. B.1 but for all comets in the red domain in Fig. 3b. The median of the distribution function with the 68.2% interval around the median value is $0.13^{+0.16}_{-0.15}$, and its mode is 0.13.

Fig. B.3. Same as Fig. B.1 but for the dust-rich comets in the K domain in Fig. 4a. The median of the distribution function with the 68.2% interval around the median value is $0.80^{+0.20}_{-0.39}$, and its mode is 0.83.

Fig. B.4. Same as Fig. B.1 but for the gas-rich comets in the K domain in Fig. 4a. The median of the distribution function with the 68.2% interval around the median value is $0.80^{+0.19}_{-0.40}$, and its mode is 0.87.

Fig. B.5. Same as Fig. B.1 but for the dust-rich comets in the red domain in Fig. 4b. The median of the distribution function with the 68.2% interval around the median value is $0.16^{+0.19}_{-0.13}$, and its mode is 0.14.

Fig. B.6. Same as Fig. B.1 but for the gas-rich comets in the red domain in Fig. 4b. The median of the distribution function with the 68.2% interval around the median value is $0.19^{+0.60}_{-0.59}$, and its mode is -0.45 .