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A composite phase function for cometary dust comae

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ABSTRACT

Comets represent the most preserved planetesimals we can nowadays study and dust is one of their major components. Once emitted in the coma, cometary dust particles represent anisotropic scatterers of the incident solar light and their nature can be investigated with remote sensing studies. Among them, the measurement of the phase function curve has a key importance in several scientific aspects. It can be inverted with theoretical and laboratory studies to derive hints on the intimate nature of the emitted dust. It is also needed in adjusting cometary dust production rates for phase angle effects when data obtained throughout large time intervals are correlated. Finally, it is useful for space instruments planning since it provides inputs for optimal exposure times for remote sensing sensors which observe the coma spanning a large range of phase angles during close approaches. This will be particularly valuable in the framework of the future ESA Comet Interceptor mission which is going to fly-by a Dynamically New Comet entering our Inner Solar System for the very first time, carrying instruments which will image the coma with different observing geometries and phase angles in a short amount of time. In order to provide an useful tool to address the aforementioned scientific topics, we used available literature data to build a new composite phase function for cometary dust comae. This was obtained fitting Henyey–Greenstein functions to the original data of 11 comets and then connecting them in a continuous way as all data values were coming from a single average comet. We then fitted our result with a compound Henyey–Greenstein curve and compared it with previous models which were not including recent literature data constituting fine follow-ups of comets at small and large phase angles. The main difference is found in the description of the forward scattering surge, where our model depicts intensity one order of magnitude larger than previous ones. This finding is extremely important since it shows that the choice of the model may have severe consequences when interpreting, or instrumentally planning, forward scattering data.

1. Introduction

Dust is one of the major components in cometary nuclei, the most preserved planetesimals we can nowadays study to infer knowledge on our solar system initial stages of formation. Once emitted in the coma, cometary dust particles represent anisotropic scatterers of the incident solar light.

Among remote-sensing studies of cometary dust, the measurement of the phase function curve, i.e. a parameter proportional to the measured intensity against the phase angle α of observation, has a key importance in several scientific aspects. Once inverted with theoretical and laboratory techniques it gives hints on the intimate nature (size, size distribution, shape, and composition) of coma particles (e.g. Bertini et al., 2007; Levasseur-Regourd et al., 2018; Moreno et al., 2018, and Frattin et al., 2019). It is also needed in adjusting cometary dust production rates for phase angle effects when data obtained throughout large time intervals are correlated (e.g. Bertini et al., 2009; Opitom et al., 2015, and Woodward et al., 2021). Finally, it is useful for space instruments planning since it provides inputs for optimal exposure

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times for remote sensing sensors which observe the coma spanning a large range of phase angles during close approaches. This will be particularly valuable in the framework of the future ESA Comet Interceptor mission, on the track to launch in 2029, which is to fly-by a Dynamically New Comet entering our Inner Solar System for the very first time or an interstellar object (Jones et al., 2024). The mission is composed by a main spacecraft and two smaller probes which will offer in-situ multi-point observations. The three probes will experience a wide range of phase angles during the encounter, essentially covering most of the range from 0° to 180°, within the safety constraints of the spacecraft and instruments. The mission will approach its target at low phase angle and, tracking the nucleus, will image the coma after flyby when the phase angle will be the highest. Moreover, one of the small probes will be equipped with the innovative Entire Visible Sky (EnVisS) camera which will map the intensity and the degree of linear polarization and polarization angle orientation of light scattered by dust particles in the comet coma with an extended phase angle coverage (Da Deppo et al., 2024). The mission constitutes an operational challenge due to the fast nature of the fly-by (the relative velocity being ∼ 50 km/s) and all operations will have to be carefully scheduled long in advance. In this aspect, it is fundamental to understand the influence of the large variation of phase angle on final data since exposure times will vary widely during the encounter and should be timed appropriately to ensure that each observation is correctly exposed.

The retrieval of a proper dust phase function starting from photometric intensity measurements has to preserve the dependence on intrinsic scattering properties of cometary dust versus phase angle of observation once other undesiderable dependencies affecting the measurements are taken into account and simplifying assumptions are made.

As underlined in Bertini et al. (2017), ground-based observations of cometary comae present usually a two-fold problem. First, a single object is rarely seen with different observing geometries covering a large range of phase angles, being observations at large phase angles, in the forward scattering region, quite rare due the small angular distance from the Sun. Secondly, in order to correlate measurements taken at different times, the assumption that the emitted dust maintains the same scattering properties over time (i.e. the same intimate nature) has to be done.

Moreover, the level of cometary activity (i.e. the amount of dust within a photometric aperture related to a fixed cometocentric distance) affects the intensity measurements and should be removed to compare data taken at different phase angles and heliocentric distances. Needless to say, the removal is strongly dependent on the coma model used. The most usual way to address this topic is measuring the albedo of the scatterers as the ratio of the apparent intensity in the visible range due to scattering of solar radiation and the apparent thermal emission in the infrared due to reradiation of the absorbed component. Both components are supposed to be directly proportional to the amount of dust in the photometric aperture. Moreover, the infrared component is supposed to be isotropic, while the visible one is not, so the aforementioned ratio maintains the dependance on the scattering properties of scatterers versus the phase angle of observation, getting rid of the cometary activity at different phase angles (Gehrz and Ney, 1992). Even when discussing the case of fast measurements within a coma during a space mission, as the ones related to Rosetta OSIRIS data in Bertini et al. (2017, 2019) which had the advantage of removing any evolution of the activity as a function of heliocentric distance, the issue of possible different optical thickness in the coma at different sampling α stations due to a non-uniform distribution of dust in the sun-ward versus anti-sun-ward direction can bias a proper phase function retrieval. This was demonstrated recently by Keiser et al. (2024), showing that an asymmetry in the dust emission distribution from the cometary nucleus can lead to large differences in the column density as a function of phase angle. Assuming all other dust physical properties are equal, there could thus be as much as 1.5 orders of magnitude more particles in the direction of large phase angles than at small phase angles. Therefore, the phase function could be heavily biased by this heterogeneous distribution of dust. Crucially, the difference in dust column density with phase angle closely follows the dust emission distribution on the surface. For example, for constant emission in all directions, there is no bias in the dust column density, while if there is some day versus night side asymmetry, it will be reflected in the dust column density. However, this may not be a major issue for all comets. For instance, considering again comet 67P/Churyumov-Gerasimenko studied by Rosetta, Gerig et al. (2020) measured the ratio between the coma brightness on the day and night sides in OSIRIS images, finding values between 2 and 4 depending on the heliocentric distance. Similarly low values were measured for other comets (e.g., 3.2 for 1P/Halley (Keller and Thomas, 1989), and 1.7 for 19P/Borrelly (Ho et al., 2007)). Combining these measurements with the theoretical study of Keiser et al. (2024) suggests that there should not be a significant bias introduction by the dust distribution of 67P/Churyumov-Gerasimenko on the phase function. At most, it is likely on the order of a factor 2-4, which is much smaller than the observed difference between the forward and backward scattering.

In this paper we present our work in using available literature data to build a new composite phase function for cometary dust comae which can be useful for the aforementioned scientific purposes.

2. Literature phase function data

Cometary comae dust particles are well known not to be isotropic scatterers. The dust coma backscattering ratio, or enhancement (BSE), defined as the ratio of the phase function curve at $\alpha = 0°$ and 30°, has scattered values in the approximate range [2–3.5], as reported in Bertini et al. (2019). Moreover, as summarized in Strøm et al. (2020), there is a very strong forward scattering phase effect that can enhance the dust brightness by a factor 1000 or more at phase angles above 175°.

A proper comparison of cometary phase function data present in literature is anyway not straightforward, since scientists use different parameters to measure the phase function. The phase function may be reported as an albedo curve, depending on the ratio between the observed fluxes in the visible and in the infrared (e.g. Gehrz and Ney, 1992, and the data collection in Kolokolova et al., 2004 and in Woodward et al., 2021), as an intensity curve (e.g. Grynko et al., 2004), as an absolute magnitude curve (e.g. Moreno et al., 2012), as a magnitude correction (e.g. Hui, 2013), or a reflectivity curve (e.g. Bertini et al., 2017, 2019).

Works by Kolokolova et al. (2004) and, more recently, Woodward et al. (2021) tried to compare available data in a common albedo versus phase angle format. These compilations are including also few data points from single comets but they are missing more recent interesting data and expressing the coma phase function with different parameters rather than albedo.

As a first step in our work we searched for updated literature entries regarding cometary phase functions with several data points for each comet. Our findings are reported in Table 1, where information on the comets dynamical types, type of phase functions, and observational geometries are provided for the objects used in this study.

We underline that all original data in the used literature sample are refereed to the scattering properties of cometary coma dust grains only. Original citations considered, applying several methodologies, the possible contribution of gas emissions to be negligible.

Moreover, the possible dependance of the phase function data on the different cometary activity level throughout the observations was ruled out by the authors.

Table 1
List of comets used in this work. Columns are: name of the comet, orbital type from the JPL Small-Body Database, phase function type, phase angle range of the observations, and literature reference.

Comet	Orbital type	PF type	α Range [°]	Reference
22P/Kopff	JFC	Absolute Mag.	3–39	Moreno et al. (2012)
P/2003 T12 (SOHO)	JFC/NEO	Mag. Correction	129–178	Hui (2013)
C/1975 V1-A (West)	Hyperbolic	Albedo	30–146	Zubko et al. (2014)
C/1980 Y1 (Bradfield)	Near parabolic	Albedo	48–149	Gehrz and Ney (1992)
96P/Machholz 1	JFC/NEO	VIS	116–156	Grynko et al. (2004)
47P/Ashbrook-Jackson	JFC	Normalized Mag.	1–25	Meech and Jewitt (1987)
38P/Stephan-Oterma	Halley	Normalized Mag.	3–29	Meech and Jewitt (1987)
C/1980 E1 (Bowell)	Hyperbolic	Normalized Mag.	0–17	Meech and Jewitt (1987)
C/1995 O1 (Hale-Bopp)	Near parabolic	Albedo	22–46	Mason et al. (2001)
67P/Churyumov-Gerasimenko	JFC/NEO	J Albedo	13–38	Hanner et al. (1985)
C/1975 N1 (Kobayashi–Berger–Milon)	Hyperbolic	Albedo	49–79	Gehrz and Ney (1992)

3. A composite approach

In order to provide an average phase function for cometary comae, we decided to put together all useful data we found in literature, considering an average trend of comets belonging to different dynamical classes.

Another important choice was to take into account only ground- or space-based observations which were not obtained within a coma, i.e. we considered data coming from instruments sampling comets from large distances.

As similarly noted in Schleicher (2010a), we do not consider our approach as a definitive result, but rather appropriate for performing first-order adjustments to dust measurements for changing phase angle.

This was performed firstly obtaining all phase function data from plots and tables present in the works cited in Table 1 and then maintaining the obtained values, for each single comet, if the data were proportional to the scattered intensity (i.e. in the form of albedo or intensity measurements). If original data were reported in magnitudes (absolute magnitude, magnitude correction, or normalized magnitude), we extracted a parameter proportional to the scattered intensity using the classical formula connecting intensity and magnitude. This preserved the aspect ratio of the intensity data for each comet.

The next step was choosing proper normalization factors to compare all literature data points in a single plot.

In order to perform this, we needed bona fide fit functions which allow common normalizations.

A famous mathematical approximation for the angle-dependent scattering behavior of small particles is the Henyey–Greestein (hereafter HG) function (Henyey and Greenstein, 1941). This function was used to model particle scattering in a large variety of astrophysical environments (see the review in Marcus (2007)). More recently, HG modeling was also used to approximate the scattering behavior of cometary comae particles (Schleicher, 2010a; Hui, 2013).

The HG function is defined as:

$$p_{HG}(\theta, g) = \frac{1}{4\pi} \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta)^{3/2}} \tag{1}$$

where θ is the scattering angle, complementary to the phase angle, and

$$g = 2\pi \int_0^\pi p_{HG}(\theta, g)\cos\theta \sin\theta d\theta = \langle\cos\theta\rangle \tag{2}$$

is the so-called asymmetry factor, i.e. the mean cosine of the scattering angle of a set of single-scattering events, ranging from −1 to +1.

The function $p_{HG}(\theta, g)$ is normalized by default so that the flux integrated over a whole sphere is set to unity. This allows the conservation of the modeled flux, since scattered radiation cannot exceed the incident one.

Following the steps described in Marcus (2007), a HG function normalized at $\theta = 90°$ can be used:

$$P_{HG}(\theta, g) = \frac{p_{HG}(\theta, g)}{p_{HG}(90°, g)} = \left[\frac{1 + g^2}{1 + g^2 - 2g\cos\theta}\right]^{3/2} \tag{3}$$

This function describes a forward scattering behavior if $g > 0$ or a back scattering behavior if $g < 0$.

As described above, the phase function of coma particles is characterized by a large forward scattering surge and a smaller back scattering increase.

In order to model this observed trend, a compound HG function can be shaped in the following form (Marcus, 2007):

$$D_{HG}(\theta, g) = kP_{HG}(\theta, g_f) + (1 - k)P_{HG}(\theta, g_b) \tag{4}$$

where $g_f \geq 0$ and $g_b \leq 0$ are the asymmetry factors for the forward and backscattering components, respectively. The parameter $0 \leq k \leq 1$ is a partitioning coefficient.

The function $D_{HG}(\theta, g)$ remains normalized at $\theta = 90°$ because the component HG functions are so normalized and the sum of the coefficients k and $1 - k$ is 1.

Using this methodology we then fitted the literature observational data with a single HG function if the data for the single comet were obtained in the forward or backscattering regime only (i.e. with phase angles values larger or smaller than 90°, respectively) and with a compound HG function if the data were belonging to the intermediate phase angle regime (i.e. taken at phase angles smaller and larger than 90°).

Since literature input data are not normalized, we used a multiplication constant, different for each comet, in order to perform a convergent HG fit to the input data. Each comet dataset was then divided by the correspondent multiplication constant, derived from the HG fit, providing this way a normalization at $\theta = 90°$ of the fit curve describing the dataset itself.

The results of this process are portrayed in the composite Figs. 1, 2, and 3, where original data for each considered comet are displayed together with the corresponding HG fitting function at small, intermediate, and large phase angles, respectively. Comets 22P/Kopff, hereafter 22P, and P/2003 T12 (SOHO), hereafter SOHO, constitute the largest datasets at small and large phase angles, respectively. In particular, comet SOHO represents the most complete comet tracking at large phase angles published so far in literature. These two comets were not included in previous cometary collections. The best HG fit coefficients for each comet are then displayed in Table 2 together with corresponding statistical uncertainties. Comets 96P/Machholz 1 and C/1975 N1 (Kobayashi–Berger–Milon), hereafter K-B-M, show best g values with large uncertainties due to the fact that such values are very close to the asymmetry factor superior limit. Nevertheless, the fit converged in both comets. Therefore, we decided to maintain these

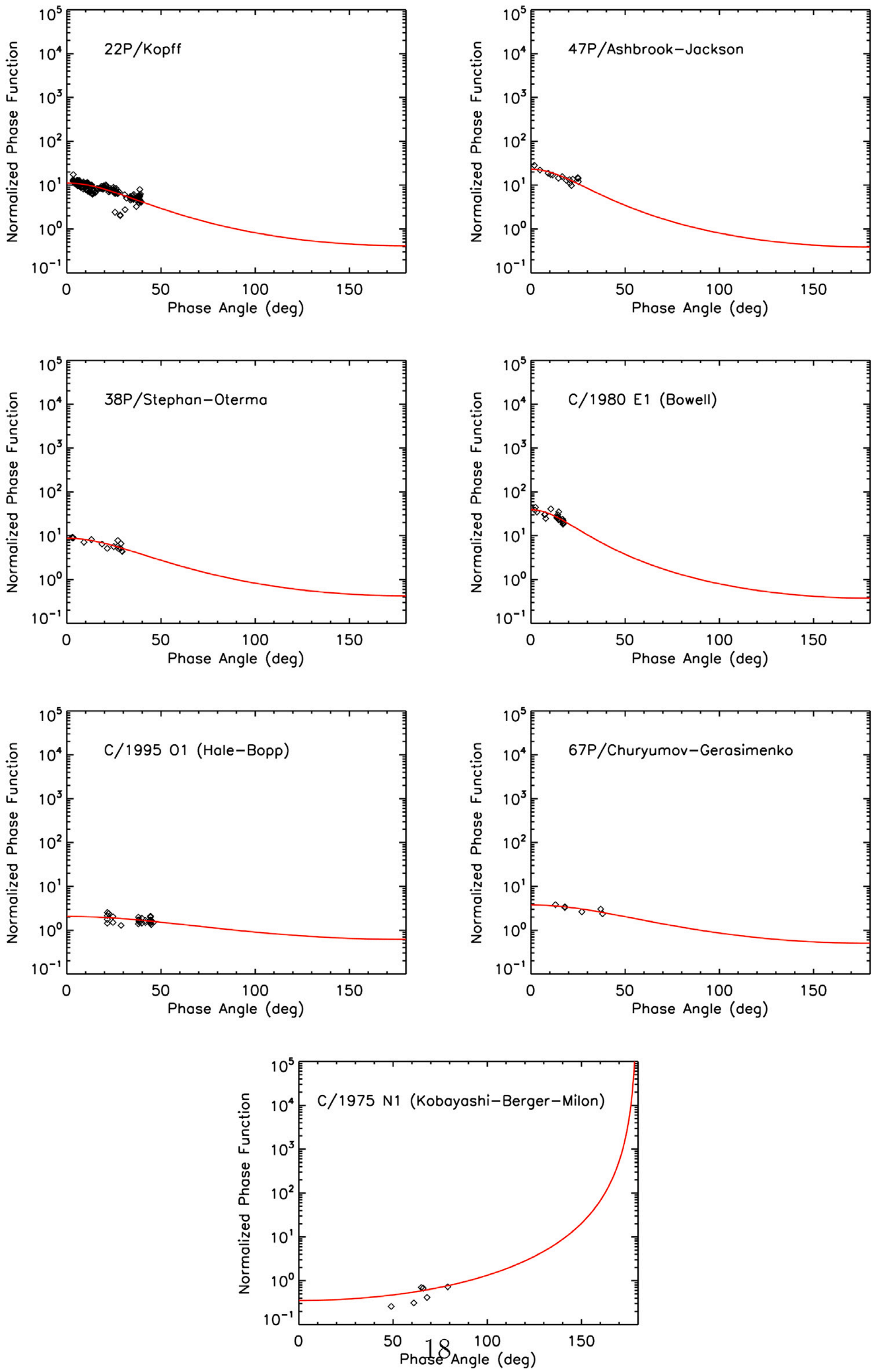

Fig. 1. Normalized phase function data for the 7 comets with data at low phase angles considered in our study, together with their HG fit curves (red lines).

two comets in the used sample. Moreover, we note that comet K-B-M represents a unique trend, since it shows an increase of intensity with the phase angle regardless the fact that its data points are obtained when $\alpha < 90°$, where instead usually the phase function decreases increasing the phase angle. Despite this unique trend, we maintained these last data points in our collection.

As an additional step we connected the single fitting curves two by two, in order to shape the final dataset in the most continuous way. This was performed considering first the fit HG curve of comet C/1975 V1-A (West), hereafter West, as a starting point. Comet 22P was then connected normalizing its fitting curve to the value of comet West fitting curve in the middle of the common interval of phase angles where data were taken. Its data were scaled accordingly. The same process was performed for comet SOHO. The scaled fit curves of comets West and SOHO became the reference fit for small and large phase angle range, respectively. Further comets with data in

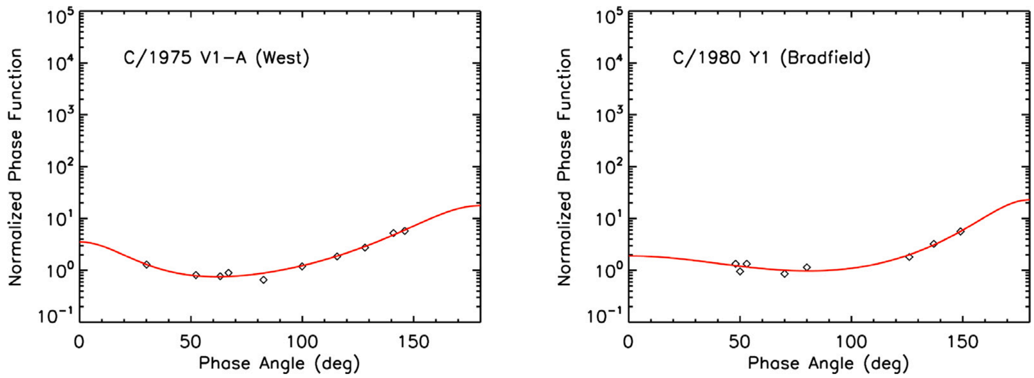

Fig. 2. Normalized phase function data for the 2 comets with data at intermediate phase angles considered in our study, together with their HG fit curves (red lines).

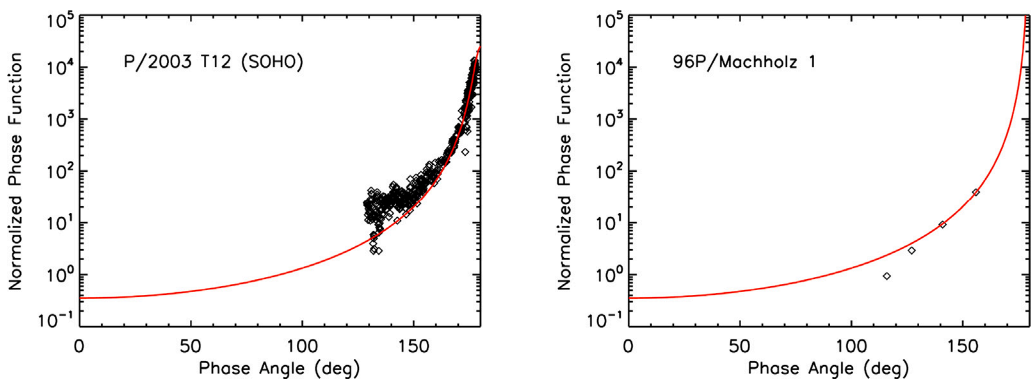

Fig. 3. Normalized phase function data for the 2 comets with data at large phase angles considered in our study, together with their HG fit curves (red lines).

Table 2
Best HG fit parameters and related uncertainties for the comets included in our study.

Comet	g	k	g_f	g_b
22P/Kopff	−0.5003 ± 0.0139	–	–	–
P/2003 T12 (SOHO)	0.9529 ± 0.0012	–	–	–
C/1975 V1-A (West)	–	0.910 ± 0.085	0.572 ± 0.038	−0.639 ± 0.273
C/1980 Y1 (Bradfield)	–	0.531 ± 0.180	0.657 ± 0.063	−0.317 ± 0.226
96P/Machholz 1	0.9999	–	–	–
47P/Ashbrook-Jackson	−0.5921 ± 0.0336	–	–	–
38P/Stephan-Oterma	−0.4653 ± 0.0367	–	–	–
C/1980 E1 (Bowell)	−0.6495 ± 0.0265	–	–	–
C/1995 O1 (Hale-Bopp)	−0.1991 ± 0.0678	–	–	–
67P/Churyumov-Gerasimenko	−0.3255 ± 0.0686	–	–	–
C/1975 N1 (Kobayashi–Berger–Milon)	0.9986	–	–	–

the backscattering regime were similarly normalized to the value of comet 22P fitting curve in the middle of the common interval of phase angles. Comet 96P/Maccholz 1, with data in the forward scattering, was connected to the fit curve of comet SOHO. Finally, comet C/1980 Y1 (Bradfield) was connected with the reference West fitting curve.

The final result was a single common dataset of 736 phase function values coming from 11 comets considered all together as literature data were belonging to a unique average comet (Fig. 4).

3.1. Analytical fit

After having obtained a composite dataset, we performed its analytical fit using a compound HG function as in Eq. (4).

The final fit is showed in Fig. 5 both in black and white color and color-coded to identify the contribution of single comets. It is evident the strong influence of comet SOHO data in the fit at large phase angles. The best-fit parameters values resulted to be: $k = 0.80$, $g_f = 0.944$, and $g_b = -0.542$, after having identified a proper multiplication constant to allow the fit to be normalized at unity at 90° of phase angle.

The analytical fit reproduces the observational scattering properties of cometary dust reported at the beginning of Section 2, being characterized by a BSE = 2.0, within the range [2 – 3.5], and by a large forward scattering enhancement which can be quantified as ∼ 12,000 between 90° and 180° of phase angle.

4. Comparison with other cometary dust phase function models

Our results can be compared to other models used to reproduce the phase function of cometary dust comae.

Among them, we were considering the Marcus (2007) and Schleicher (2010b) ones.

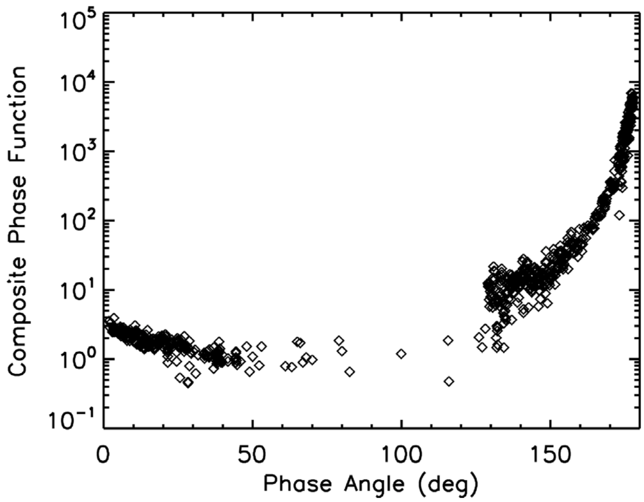

Fig. 4. Composite phase function of cometary comae obtained with 736 data points belonging to 11 comets.

Marcus was producing a composite HG function fitting data from 5 comets (C/1927 X1 (Skjellerup-Maristany), C/1975 V1 (West), C/1980 Y1 (Bradfield), 96P/Machholz 1, and C/2004 F4 (Bradfield)) and introducing an additional parameter, δ_{90}, representing the dust-to-gas light ratio in the coma as viewed at a phase angle of 90°. This led to best fit parameters $g_f = 0.9$, $g_b = -0.6$, $k = 0.9$, and $\delta_{90} = 1$ and 10 in the case of an usual or dusty comet, respectively.

Schelicher found a composite curve splicing a quadratic fit of comet 1P/Halley data at small phase angles in Schleicher et al. (1998) with a Marcus curve at large phase angles, using $\delta_{90} = 100$ when solving Marcus equation, i.e. effectively making gas contamination negligible in the derived phase function.

The comparison of the three different models can be see in Fig. 6, where all phase curves are normalized at $\alpha = 90°$.

Schelicher and Marcus models produce very similar results with tiny differences, especially when the case of a dusty comet, where gas contamination in the coma signal at visible wavelength is negligible, is considered. Schleicher model restitutes a BSE = 2.5 and a forward scattering enhancement between 90° and 180° of $\sim 2,200$. Marcus model is characterized by smaller BSE = 1.4 and 1.9 and forward scattering enhancement equal to $\sim 1,100$ and 2100, in the usual and dusty comet case, respectively.

Our findings present consistent BSE values with previous models, although there are small factors of difference when the ratio of the phase function at 0° and 90° of phase angle is considered (e.g. 3.35 and 1.86 in our and Schleicher model, respectively), mainly due to the innovative inclusion of comet 22P data. Our model is instead characterized by a much larger forward scattering enhancement that quantifies as an order of magnitude larger if we take into account data between 90° and 180° of phase angle. This is due to the innovative inclusion in our collection of the large dataset of comet SOHO, which represents the most detailed dataset for comets observed at high phase angles so far. The choice of the model may have therefore severe consequences when interpreting, or instrumentally planning, forward scattering data.

5. Summary and conclusions

Dust is one of the major components in cometary nuclei, the most preserved planetesimals we can nowadays study to infer knowledge on our Solar System initial stages of formation.

Once emitted in the coma, cometary dust particles represent anisotropic scatterers of the incident solar light.

Among remote-sensing studies of cometary dust, the measurement of the phase function curve has a key importance in several scientific aspects. It can be inverted with theoretical and laboratory studies to derive hints on the intimate nature of the emitted dust. It is also needed in adjusting cometary dust production rates for phase angle effects when data obtained throughout large time intervals are correlated. Finally, it is useful for space instruments planning since it provides inputs for optimal exposure times for remote sensing sensors which observe the coma spanning a large range of phase angles during close approaches. This will be particularly valuable in the framework of the future ESA Comet Interceptor mission, to be launched in 2029, which is going to fly-by a Dynamically New Comet entering our Inner Solar System for the very first time or an interstellar object, carrying instruments which will image the coma with different observing geometries and phase angles.

In order to provide an useful tool to address the aforementioned scientific topics, we used available literature data to build a new composite phase function for cometary dust comae.

This was obtained fitting HG functions to the original data of 11 comets and then connecting them in a continuous way as all data values were coming from a single average comet.

Our final result was then fitted with a compound HG curve and compared with previous models which were not including recent literature data constituting fine follow-ups of comets at small and large phase angles. We found similar values for the BSE, although with larger values of the phase function increment between 90° and 0° of phase angle. Most noticeably, our model depicts a forward scattering surge (measured as the ratio of the phase function between 90° and 180° of phase angle) one order of magnitude larger than previous models.

This finding is extremely important since it shows that the choice of the model may have severe consequences when interpreting, or instrumentally planning, forward scattering data.

CRediT authorship contribution statement

Ivano Bertini: Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jean–Baptiste Vincent:** Writing – original draft, Validation, Formal analysis, Conceptualization. **Raphael Marschall:** Writing – original draft, Conceptualization. **Fiorangela La Forgia:** Writing – original draft, Formal analysis. **Alessandra Mura:** Writing – original draft, Formal analysis. **Laura Inno:** Conceptualization. **Stavro Ivanovski:** Conceptualization. **Michael Küppers:** Conceptualization. **Cecilia Tubiana:** Conceptualization. **Vladimir Zakharov:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

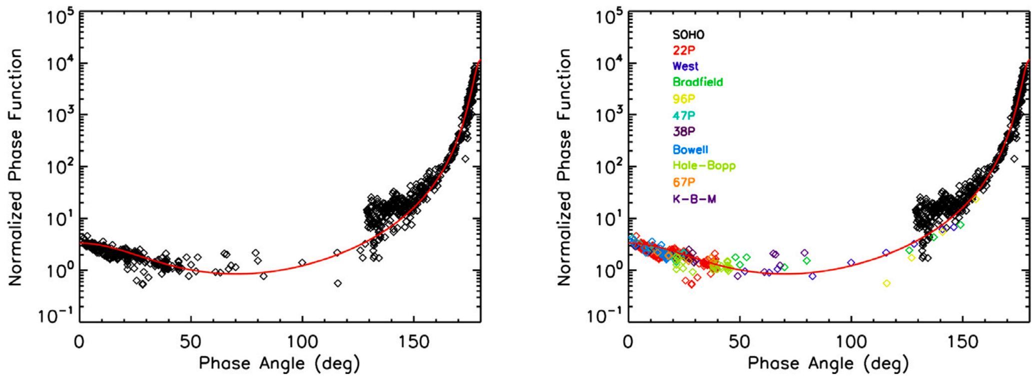

Fig. 5. Final compund HG fit (red curve) to all data points (black) on the left and color-coded for the different comets on the right.

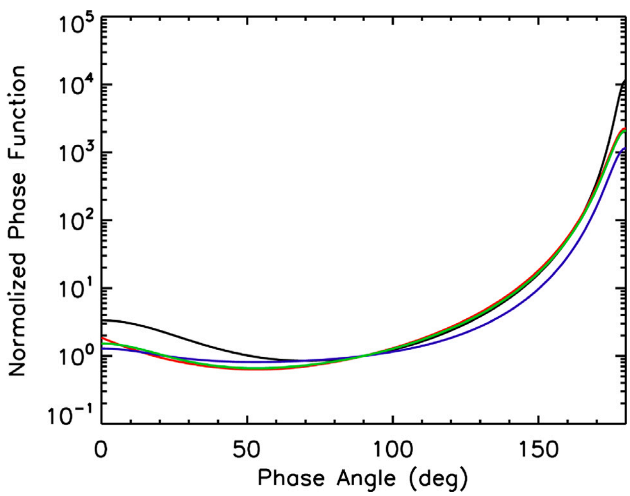

Fig. 6. Comparison between our findings (black line) and Schleicher (red line) and Marcus usual (blue line) and dusty comet (green line) models.

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