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On the reflectance of dust in comets

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ABSTRACT

Reflectance of cometary dust is a key parameter used in the characterization of comets. In the literature, the reflectance of single-scattering cometary dust particles is widely assumed to be the same as that of the cometary nucleus. We discuss this assumption and demonstrate its inconsistency with photometric observations of comets, laboratory optical measurements, and numerical simulation of light scattering from single-scattering dust particles and particulate surfaces composed of the same particles. We estimate the reflectance of cometary dust particles using a comprehensive physical model of polarization measured in comets over wide range of phase angle and at different wavelengths in the visible. The model predicts that the reflectance of dust in comets inversely correlates with their maximum of positive polarization $P_{\max}$. We find that even the darkest dust particles appearing in comets with the highest $P_{\max}$, reflect considerably more incident solar-radiation energy, up to 200%, compared to what is thought for cometary nuclei. We also find that the reflectance retrieved from polarimetry in the visible appears in good quantitative accordance with previous estimations from infrared observations of comets. Our findings suggest that the dust production of comets is currently overestimated and may require revision.

1. Introduction

Reflectance or albedo of cometary dust is a key parameter in the analysis of photometric observations of comets, as it is needed to convert the apparent magnitude of a comet into the amount of its dust and, thus, estimate the dust production rate of its nucleus (e.g., [1]). Despite its importance, the reflectance is still poorly known. In the literature, the reflectance of cometary dust often is adapted from what was measured in situ in cometary nuclei (e.g., [2–4], and other). However, validation of this approach meets significant difficulties, resulting in large uncertainties in the retrievals of dust production rates in comets.

One of the issues in characterizing cometary dust is that comets are dynamic, and the dust in their coma changes with its orbit. At large distances from the sun, cometary activity is weak, as is the solar wind, and the size distribution of the particles in the coma are much larger than when the comet is nearer the sun. It is when the comet is near the sun that dust-production becomes significant, and it is this epoch that is the focus of our work. In the region close to perihelion, comets have not only been monitored extensively, but also have been probed in situ. The size distribution of comae particles is typically characterized using a power-law size distribution r^{-n} where r corresponds with particle size and the power index n is not constant. For example, in the domain of submicron and micron-sized particles the power index in Comet 1P/Halley ranges from 1.5 up to 3.4 [5]; i.e., the relative number of small particles dominates over the number of large particles. Nevertheless, at $n \leq 3$, the integral geometric cross section is governed by the upper limit of the size distribution; i.e., the large particles dominate the light-scattering response. However, in situ measurements also demonstrate that the power index n grows with particle size r. In Comet Halley, for instance, Mazets et al. [5] found different particle distributions in different portions of the coma from both the Vega 1 and 2 trajectories. They noted that for smaller dust particles, $10^{-16} < m < 10^{-12}$ g, the power index $n \sim$ 1.5–2.5; however, for larger particles, they found a significant drop in number concentrations at all locations. For particles whose mass is greater than 10^{-12} g, they found $n \sim 3.4$ [5], which would result in the smaller particles dominating the light-scattering response. Assuming bulk material density of 0.5 g/cm^3, 10^{-12} g particles have dimensions on the order of 4 μm.

Similar distributions have been determined using the *Stardust* instrumentation to examine the dust of Comet Wild 2. For in-

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stance, Green et al. [6] used the *Stardust Dust Flux Monitor Instrument* (DFMI) and found tremendous variations in the particle distributions in time and spatial scales, with cumulative mass distributions $m^{-\gamma}$ and γ ranging from 0.3 to 1.1, which correspond to power indices n ranging from 1.9 to 4.3. They suggest a single mass distribution $\gamma = 0.85 \pm 0.05$ that corresponds to $n = 3.55$, which is similar to the results retrieved from Comet Halley [5]. Green et al. [6] note that the mass index "*implies a coma dominated by scattered light from small particles at 81P/Wild 2.*"

Unfortunately, due to the mission parameters that dictated relatively low speeds between Comet 67P/Churyumov-Gerasimenko and the Rosetta spacecraft, the GIADA impactor was not sensitive to dust particles smaller than several tens of microns [7], and could only measure particle distributions with a lower size limit of approximately 0.1 mm. While Rosetta's Micro-Imaging Dust Analysis System (MIDAS) did have the capability to characterize micron-size particles [8], such particles were not detected [9], most probably because the electrostatic potential of the spacecraft prevented small grains from reaching the collection plate as discussed by Fulle et al. [7].

The dynamic nature of cometary comae dust properties adds further complications to the assumption that its reflectance is similar to that of the nucleus. In the next section, we briefly discuss the principal inconsistencies of the approach with the results of astronomical observations, laboratory optical measurements, in situ findings, and numerical simulations of light scattering by irregularly shaped particles. In Section 3, we develop an alternative approach, inferring reflectance of cometary dust from modeling polarimetric observations of comets in the visible. In Section 4, we consider our results in the general context of cometary physics and compare our findings with previous estimations of the reflectance of cometary dust in the near-infrared (e.g., [9]). The article is concluded in Section 5 with a brief summary.

2. Inconsistencies in the current estimations of the reflectance of cometary dust

The reflectance of a cometary dust particle $A_p(\alpha)$ is defined as a product of its geometric albedo A and the phase function $p(\alpha)$ normalized at exact backscattering [11]:

$$A_p(\alpha) = A \times p(\alpha)/p(0^\circ) \tag{1}$$

where α is the phase angle. The geometric albedo A characterizes the ratio of the intensity of the light backscattered from a target particle over what is a fully reflecting Lambertian scatterer with the same projected area and in the same geometry of illumination/observation. Hanner et al. [11] considered two types of references, a non-absorbing isotropic scatterer and a white Lambertian disk. Nowadays, the latter definition is predominantly considered in the literature and, therefore, it is a subject of the present consideration. The geometric albedo defined with respect to the Lambertian disk is expressed as follows:

$$A = M_{11}(0^\circ)\pi / \left(k^2 G\right). \tag{2}$$

Here, $M_{11}(\alpha)$ denotes the total intensity element of the Mueller scattering matrix [12], G denotes the geometric cross section of the particle, and k denotes wavenumber. Note also, in [11], the parameter $A_p(\alpha)$ was conditionally named as *an albedo at any angle*.

In the literature, one can find numerous examples in which the geometric albedo of single-scattering cometary dust particles is adjusted to what is thought to be the geometric albedo of cometary nuclei; typically, $A \approx 0.03$–0.05 (e.g., [2–4]). Below we demonstrate the difficulties and inconsistencies, such an assumption meets. However, first, it is worth noting that the geometric albedo of a bare cometary nucleus is poorly known. The reflectance of a cometary nucleus was unambiguously measured only in six comets visited by spacecrafts. Except for the latest case of Comet 67P/Churyumov–Gerasimenko, the other five comets were studied on flyby trajectories that place some limitations on the geometry of their observations. Although in some cases it was possible to infer a phase dependence of the reflectance of the nucleus over a wide range of phase angles (e.g., [13]), neither of the five comets was observed at sufficiently small phase angles of a few degrees or smaller. In these circumstances, the geometric albedo can be estimated only with a radiative-transfer model. Such modeling is accompanied with simplifications and approximations (e.g., [14]). As a consequence, the geometric albedo of the nucleus is retrieved with uncertainty and, therefore, it should be considered with caution [15]. The investigation of the reflectance of Comet 67P/Churyumov–Gerasimenko by *Rosetta* is a unique case. While the space probe was orbiting the 67P/Churyumov–Gerasimenko nucleus, it was possible to gather significant information on its reflectance at various illumination/observation conditions. This resulted in the normal reflectance $A_p(0^\circ) = 0.06 \pm 0.003$ at the wavelength $\lambda = 0.55\,\mu\text{m}$ [16,17] that significantly exceeds (by at least 50%) what had been obtained in situ in other cometary nuclei (e.g., [3]).

On a fundamental level, there are significant shortcomings in assuming that the geometric albedo of a single dust particle is the same as that of the extended nucleus surface. For this to be true, the light-scattering characteristics other than the geometric albedo, e.g., photometric color and phase function, also must be similar in the coma and nucleus. While there may be similarities, we know that the light-scattering phase functions for such systems are significantly different. This has been demonstrated in both modeling [18] and experimental [19] studies of terrestrial samples. This also has been demonstrated in cometary observations. For instance, a comparison of photometric color of the nucleus and coma measured simultaneously in [3] show distinct differences. In this case, nuclei are characterized with the color index (R – I) (Table 4 in the original paper); whereas, comae are characterized with the normalized spectral reflectivity gradient S' [0.67 µm, 0.792 µm] (Table 6 in the original paper). Note that the definition of the normalized spectral reflectivity gradient used in [3] is identical to the color slope introduced in [20]. The color slope can be expressed directly through the color index (R – I) as follows:

$$S' = \frac{10^{0.4(R-I)} - 1}{10^{0.4(R-I)} + 1} \cdot \frac{2}{\lambda_I - \lambda_R}, \tag{3}$$

where, $\lambda_I = 0.792\,\mu\text{m}$ and $\lambda_R = 0.67\,\mu\text{m}$ are the effective wavelengths of the I and R filters, respectively. We measure the color slope in percent per 0.1 µm.

Using Eq. (3), we compute the color slope S' for the nuclei of seven comets and present the results in the fourth column in Table 1. In the fifth column we reproduce S' for cometary coma that is directly adapted from [3]. As one can see, only in one comet out of seven, 106P/Schuster, do the color slopes of the coma and nucleus nearly coincide with one another. In three comets, the nucleus is noticeably redder compared to the coma, and in the other three comets it is noticeably bluer. Thus, in comets there appears to be no systematic correlation between the color of the coma and the nucleus. Since there is no apparent correlation between the colors, the wavelength-dependent geometric albedos must be different for the two systems.

The light-scattering responses from cometary comae and nuclei may differ because they could be populated by particles with different chemical and/or physical properties. For instance, dust particles forming a coma may be only partially representative of those lying on the nucleus surface. Considerable quantities of ejected particles, up to 86% by volume, can originate from the subsurface volume and have different chemical composition from the nucleus surface [21].