

REFLECTANCE OF COMETARY DUST INFERRED WITH POLARIMETRY. E. Zubko^{1,2}, G. Videen^{3,4}, and Yu. Shkuratov², ¹School of Natural Sciences, Far Eastern Federal University, Vladivostok, Russia, evgenij.s.zubko@gmail.com, ²Institute of Astronomy, V. N. Karazin Kharkov National University, Kharkov, Ukraine, ³Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301, USA, gorden.videen@gmail.com, ⁴Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783, USA.

Introduction: The apparent magnitude of a comet is dependent on its gas and dust production. When observing a comet with filters isolated from gaseous emission, the apparent magnitude can be interpreted solely in terms of light scattering by its dust. In theory, this makes it possible to estimate the total amount of dust within the field of view. In practice, however, such an estimation is difficult due to poor knowledge of the reflectance of cometary dust particles.

The reflectance of cometary dust particles $A_p(\alpha)$ is defined as a product of the geometric albedo A to phase function normalized in the backscattering $p(\alpha)/p(0)$, where α denotes the phase angle. The geometric albedo is measured as a ratio of intensity of the light backscattered from target particle over that of a Lambertian disk of the same projected area [1].

It is currently thought that A_p of cometary dust particles in visible is ~ 0.05 near backscattering and half of this value at side-scattering angles $\alpha \sim 90^\circ$ (e.g., [2,3]). However, this estimation arises from a 35-year-old experimental study of the electromagnetic scattering by irregularly shaped particles [1].

The technique utilized in [1] was indeed state-of-the-art in its time; nevertheless, it suffers from a few important shortcomings. The most important of these is that the compact and fluffy morphologies of particles investigated in [1] at various refractive indices and sizes have not demonstrated the capability to reproduce the photometric and/or polarimetric observations of comets. Thus, although the findings in [1] are widely incorporated in analyses of observations of comets, there is no compelling reason why such particles should be used over other irregularly shaped particles. Their use results in a large uncertainty in the retrieval of the amount of ejected dust. In this short note, we infer the reflectance of cometary dust particles from a model that satisfactorily reproduces multi-wavelength polarimetric observations of various comets over a wide range of phase angles [4] and has also reproduced the phase function and color measured in dust in Comet C/1975 V1 (West) [5].

Model of Polarization of Cometary Dust: Modeling the polarization in comets can place strong constraints on the characteristics of their dust. It is significant that such constraints are much stricter compared to what is obtained from just the photometric response.

For instance, in [5], it is demonstrated that the phase function of Comet West can be reproduced under the assumption of uniform chemical composition of its dust; whereas, modeling of the angular profile of the degree of linear polarization P requires the presence of at least two types of particles with noticeably different chemical composition. Therefore, it is of practical interest to estimate the reflectance of cometary dust particles that results from analyses of their polarimetric response.

We adapt the two-component model of cometary coma that is developed previously [4,5]. The constituent material in one type of particle is chosen to be weakly absorbing, i.e., with low imaginary part of the refractive index $\text{Im}(m) \leq 0.01$. Such material can be attributed, for instance, to Mg-rich silicates, an abundant species in comets (e.g., [6]). The constituent material of the other type of particle is highly absorbing and can be associated with amorphous carbon or organic matter that underwent heavy UV irradiation and/or ion bombardment. Note, carbonaceous materials are also detected in comets in considerable quantities (e.g. [6]) and fit into this latter category. For simplicity, we consider both types of dust particles having the same morphology that is modeled with the so-called *agglomerated debris particles*. These model particles have highly irregular morphology that is visually consistent with shapes of cometary dust sampled *in situ* [7]. The packing density of constituent material in agglomerated debris particles is equal to 0.236. At material density of silicates, organic matter, and amorphous carbon, the bulk material density of the agglomerated debris particles spans the range from 0.354 g/cm³ up to 0.826 g/cm³, that is representative for low-density cometary [7] and interplanetary [8] dust particles. Finally, the model accounts for polydispersity of cometary dust particles. Weakly and highly absorbing particles are assumed to obey the same power-law size distribution r^{-n} , with the power index $n \sim 2$, being also in good quantitative agreement with *in situ* findings [9]. For more details on the two-component model of coma we refer reader to [4, 5].

It appears that the two-component model may reproduce the polarimetric observations of the vast majority of comets. On the bottom in Fig. 1, we present a compilation of the observational results for 23 differ-

ent comets adapted from [4]. The interrelation between the type of symbols and specific name of comets, as well as references to the original reports of observational results, can be found in [4].

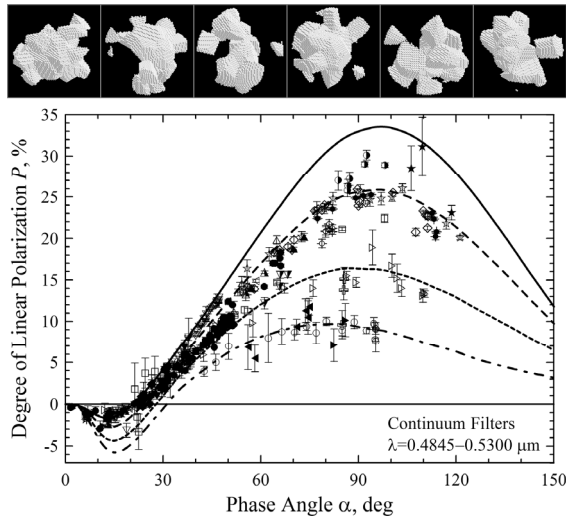


Fig. 1. Sample agglomerated debris particles (top) and polarimetric phase function of comets (bottom).

As one can see in Fig. 1, comets reveal significant dispersion in their amplitude of positive polarization P_{max} [10,11]. It is significant that the two-component model can satisfactorily reproduce polarimetric response in all the comets presented in Fig. 1 by varying only a single free model parameter, the relative abundance of highly and weakly absorbing particles. In Fig. 1, we demonstrate this with agglomerated debris particles having refractive indices $m=1.6+0.01i$ and $m=1.855+0.45i$, and obeying a power-law size distribution with $n=2.1$. The solid line reproduces the highest polarimetric response detected in Comets C/1995 O1 (Hale-Bopp) and D/1999 S4 (LINEAR). This fit is obtained with 17% (by volume) of weakly absorbing particles and 83% of highly absorbing particles. However, the decrease of P_{max} increases relative to the abundance of weakly absorbing particles. For instance, the fit to Comet C/1996 B2 (Hyakutake) shown with the dash line in Fig. 1 is obtained with 28% weakly absorbing particles; whereas, the fit to Comet C/1989 X1 (Austin) (the dot line) with 53% of weakly absorbing particles. Finally, the lowest positive polarization in Comets C/1975 N1 (Kobayashi-Berger-Milon) and 23P/Brorsen-Metcalf is reproduced with 95% weakly absorbing particles.

Reflectance of Cometary Dust: The comprehensive model of polarization discussed in the previous section yields complementary light-scattering characteristics such as single-scattering albedo, geometric albedo, phase function, etc. This makes it possible to

compute the reflectance $A_p(\alpha)$ of cometary dust particles shown in Fig. 2.

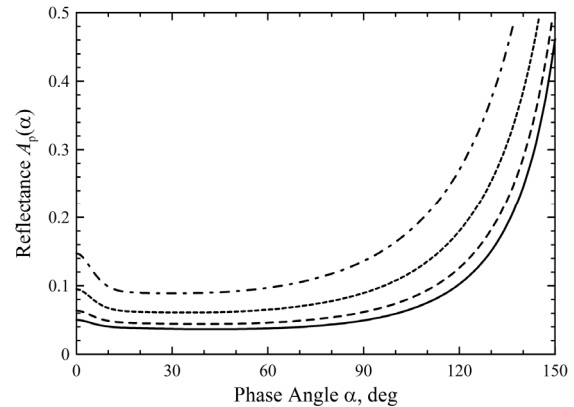


Fig. 2. Reflectance of dust particles.

As one can see in Fig. 2, dust in Comet C/1995 O1 (Hale-Bopp) reveals the lowest reflectance. Within the backscattering region, the reflectance of Hale-Bopp dust is consistent with the current standard of 0.05, while at side-scattering angles, the dust in Comet Hale-Bopp is noticeably brighter compared to the standard, $\sim 0.035-0.040$ vs. ~ 0.025 . However, the growth of population of weakly absorbing particles in comets with lower P_{max} evidently increases their reflectance. For instance, the reflectance of dust in Comet Hyakutake at side scattering is as high as 0.045–0.050. The greatest reflectance appears in the comets with the lowest P_{max} ; it can be as high as ~ 0.15 near backscattering regime and $\sim 0.09-0.10$ at side scattering regime. Thus, the reflectance is 3–4 times greater compared to the current standard.

Conclusion: Comprehensive modeling of polarization of cometary dust makes it possible to estimate its reflectance. We find that the reflectance can be up to a few times greater than the standard and can vary significantly between comets. This suggests that the dust production rate in comets can be a few times lower compared to what is currently thought.

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