Differences in polarimetric properties of cometary jets and circumnucleus halos

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Abstract

Polarimetry of comets reveals significantly higher polarization in jets than in circumnucleus halos. We hypothesize that this difference arises from distinction in the velocity of dust: particles in jets move out of a nucleus much faster than those in a halo and thus we may observe jet particles in the early stage of their evolution when they are large agglomerates of small grains fastened by a certain amount of ice; velocity of particles in a circumnucleus halo is low enough to be observed in the latter stage of evolution when ice already sublimated totally and agglomerates have been disrupted into constituent grains. Using the discrete dipole approximation we study the influence of disruption of agglomerated dust particles due to ice sublimation on their angular dependence of degree of linear polarization. We found that in a wide range of phase angles the linear polarization of agglomerates of three grains comparable to wavelength covered by ice is visibly higher than polarization of independently scattering constituent grains. This supports our interpretation of the polarimetric observations of comets.

1 Introduction

An approach of a comet to the Sun initiates its coma (a gas-dust atmosphere) whose structure is always inhomogeneous and changes with time. Frequently observed features of the coma are jets, which are high-speed fluxes of gas and dust particles ejected from the surface of the cometary nucleus. The projected velocity of jet particles on an image plane derived from observations of comets is as high as 300–500 m/s [1]. The relatively high speed of jet particles is a result of acceleration of those particles by gas drag. Polarimetry of comets shows that jets are more positively polarized compared with the circumnucleus halo – a bright cloud around a nucleus with a lower polarization [2, 3]. In the range of small phase angles ($\alpha \leq 20°$) in particular, the degree of linear polarization of jets remains substantially positive (i.e., higher), while the circumnucleus halo reveals significant negative polarization i.e., lower, up to –6% near opposition [2, 3]. The authors of [2, 3] associate the higher degree of linear polarization in jets with presence of small grains and/or fluffy aggregates; the lower linear polarization of the circumnucleus region is attributed to more compact dust particles. This seems to be a reasonable explanation because small particles as well as porous aggregates consisting of them reveal essentially higher polarization than compact micron particles which reveal prominent negative polarization branches (NPB) near backscattering [see, e.g., 4].

In this paper, we propose an alternative explanation for the difference in polarimetry of jets and a circumnucleus halo. As it was previously shown with Geometrical Optics Approximation [5, 6], high-absorbing compact irregular particles of size larger than wavelength produce only positive polarization in the entire range of phase angles. Irregular particles comparable to wavelength, however, produce a few stable areas of negative polarization [4, 8]; one of them is in the range of small phase angles. Thus, the polarimetrical difference between a halo and jets may be attributed to a change in size and composition under dust evolution. We investigate the plausibility of this explanation using the discrete dipole approximation (DDA).

2 Model of cometary dust particles

Due to high velocities in jets, we expect to observe fresh large particles preserving ice. On the contrary, particles in the rest of circumnucleus region move significantly slower than those in jets because they are not accelerated by flux of gas. Thus, we observe them in the later stage of evolution when initial large particles are already disrupted into small grains due to total losing of ice. Our interpretation is consistent with polarimetry of comet C/1995 O1 (Hale-Bopp) at a heliocentric distance of 2.9 AU and a phase angle of α=19.6°. Namely, the lengths of four bright jets ranging from 2700 to 5400 km correspond to the distances that dust particles at an average velocity of 400 m/s could cover within 2–4 hours, equivalent to the evaporation timescale for homogenous icy spheres with radius 1 μm.

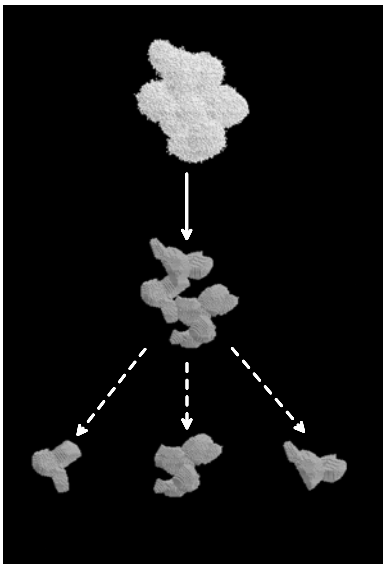

Figure 1: Example image of model particles.

In the present paper, we study the applicability of dust disruption due to ice sublimation to interpretation of the difference in polarimetry between cometary jets and a circumnucleus halo. We assume that particles freshly ejected from a cometary surface are agglomerates of a number of irregular micron grains, filled with ice. Due to this infill the freshly ejected particles could be considered as compact particles significantly larger than visible wavelengths with optically soft inclusions. For instance, refractive indices of an ice infill m=1.313+0i and silicate grains m=1.66+0.0028i at visible wavelength give us the relative refractive index of silicate inclusions in large icy particle as m=1.264+0.0021i. We guess that the features found for compact irregular particles significantly larger than wavelength are also valid, at least in some part, for large particles with optically soft inclusions. We examine here the case when initial particles consist of three irregularly shaped grains. These agglomerated particles are covered with a certain amount of ice. Note that the model fresh particles are only a few times bigger than the constituent grains and, thus, they are still comparable to wavelength.

We compute the scattering of light by particles comparable to wavelength with the DDA method [4, 7, 8]. This is a numerical approach intended for simulation of light scattering by particles comparable to wavelength. The DDA has no restrictions on the shape and internal structure of a particle and thus it is well suitable for the current purpose.

The constituent grains have been generated with help of one of the algorithms described in [4]. For a fixed set of three constituent grains, we build 24 various sample agglomerates. We study separately two kinds of constituent grains: grains of pure silicate (refractive index m=1.66+0.0028i) and grains of a silicate core and an organic mantle (m=1.5+0.1i) with the volume ratio of silicate to organic material being unity. Images of pure silicate grains and one example of the constructed agglomerate are shown in Figure 1. The bottom row shows initial grains separately, whereas the agglomerate constructed from these initial grains is shown in the middle of the figure. Images of core-mantle grains and agglomerates constructed from them are not much different from those shown on Figure 1; the agglomerates are only a little bit bigger and grains have more smoothed shape. Finally, we cover sample agglomerates by icy shell (m=1.313+0i) like it is shown in the top of Figure 1. In the case of pure silicate agglomerates the volume ratio of grains to icy shell is set 1:2 and in the case of agglomerates of core-mantle grains – 1:1. Thus both kinds of particles are covered with equal amount of ice.

3 Results of calculations

We first compute light scattering by agglomerates covered with ice shell and then we consider independent scattering by constituent grains. Comparison of two these cases allows us to estimate clearly the influence of disruption of sample particles due to ice sublimation on their scattering of light. We have examined different sizes of grains but here we present only results for 1.9 μm grains (this is the size of circumscribing sphere of the largest of three grains at a wavelength of λ=0.5 μm). All cases have been averaged over orientations so that the standard deviation of degree of linear polarization does not exceed 1.5%.

Figure 2 presents the phase dependences of the degree of linear polarization *P* for agglomerates of pure silicate grains (left panel) and for agglomerates of silicate-core organic-mantle grains (right panel). As we expected, all considered cases reveal prominent negative polarization at small phase angles. Qualitatively the same result has been previously received for other kinds of compact particles comparable to wavelength [4, 8]. At the same time, we can see that in comparison with single grains,

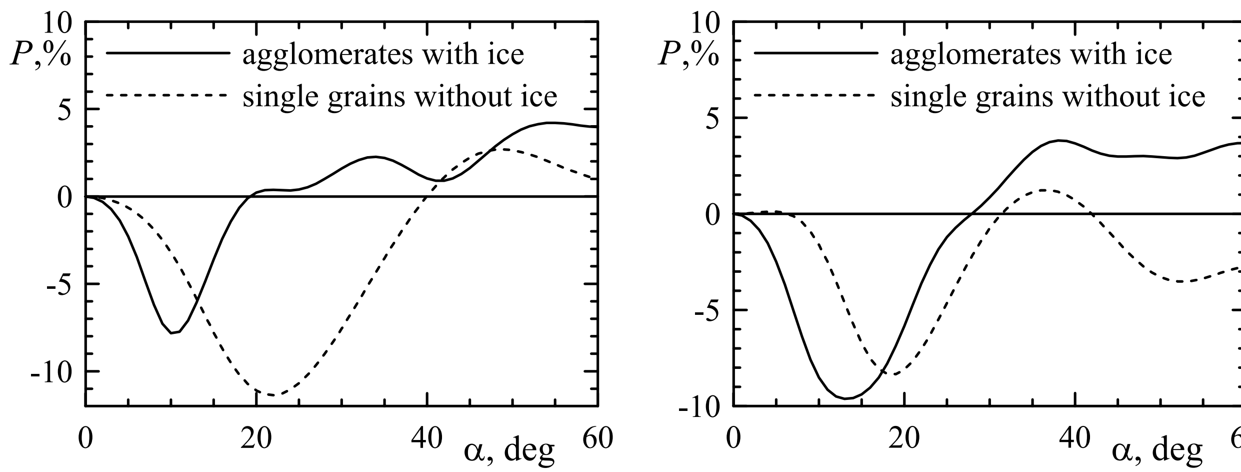

Figure 2: Phase curves of degree of linear polarization of agglomerates covered by ice and single constituent grains. Left panel: pure silicate grains. Right panel: grains with a silicate-core plus organic-mantle structure.

NPB of agglomerates covered by ice shell is shrunk to zero phase angle. The NPB of agglomerates of pure silicate grains is almost two times shallower than NPB of independently scattering grains. Thus, in a wide range of phase angles agglomerates covered by ice shell produce visibly a higher degree of linear polarization than single grains. For pure silicate grains this is the case at phase angles α=15–60° (except for a narrow region near α=45°) and for core-mantle grains α=18–60°.

4 Discussion

At phase angles α≥15°, our simulation qualitatively reproduces the observed difference in polarimetry of jets and a circumnucleus halo. In the range of smaller phase angles α<15°, our simulation does not agree with observations, but we have two reasons to suppose that a larger number of constituent grains will make the NPB of agglomerates shallower. First, as it was shown in experimental measurements of light scattering by single irregular particles and media composed of these particles, the multiple scattering between the particles strongly decreases the NPB [9]. The same dependence has been also found with a DDA simulation of light scattering by agglomerated particles [10]. Another factor is the filling of porous agglomerate by ice, which decreases single scattering by constituent grains and thus their NPB. In future we plan to involve a larger number of constituent grains in order to check our guess.

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References

[1] J. Warell, C. Lagerkvist, J. S. V. Lagerros, “Dust morphology of the inner coma of C/1995 O1 (Hale–Bopp)” Earth, Moon, and Planets, **78**, 197–203 (1997).

[2] E. Hadamcik, A.C. Levasseur-Regourd, “Dust evolution of comet C/1995 O1 (Hale-Bopp) by imaging polarimetric observations”, Astronomy & Astrophysics, **403**, 757–768 (2003).

[3] E. Hadamcik, A.C. Levasseur-Regourd, “Imaging polarimetry of cometary dust: different comets and phase angles”. J. Quant. Spectrosc. Radiat. Transfer, **79-80**, 661–678 (2003).

[4] E. Zubko, Yu. Shkuratov, N. Kiselev, G. Videen, “DDA simulations of light scattering by small irregular particles with various structure”, J. Quant. Spectrosc. Radiat. Transfer, **101**, 416–434 (2006).

[5] K. Muinonen, T. Nousianen, P. Fast, K. Lumme, and J.I. Peltoniemi, “Light scattering by Gaussian random particles: ray optics approximation.” J. Quant. Spectrosc. Radiat. Transfer, **55**, 577–601. (1996).

[6] Ye. Grynko and Yu. Shkuratov, “Scattering matrix calculated in geometric optics approximation for semitransparent particles faceted with various shapes”, J. Quant. Spectrosc. Radiat. Transfer, **78**, 319–340 (2003).

[7] A. Penttilä, E. Zubko, K. Lumme, K. Muinonen, M. A. Yurkin, B. Draine, J. Rahola, A. G. Hoekstra, Yu. Shkuratov, “Comparison between discrete dipole implementations and exact techniques”, J. Quant. Spectrosc. Radiat. Transfer, *in press* (2007).

[8] E. Zubko, K. Muinonen, Yu. Shkuratov, G. Videen and T. Nousiainen, “Scattering of light by roughened Gaussian random particles”, J. Quant. Spectrosc. Radiat. Transfer, *in press* (2007).

[9] Yu. Shkuratov, A. Ovcharenko, E. Zubko, H. Volten, O. Munoz, G. Videen, “The negative polarization of light scattered from particulate surfaces and of independently scattering particles”, J. Quant. Spectrosc. Radiat. Transfer, **88**, 267–284 (2004).

[10] E. Zubko, Yu. Shkuratov, K. Muinonen, G. Videen, “Collective effects by agglomerated debris particles in the backscatter”, J. Quant. Spectrosc. Radiat. Transfer, **100**, 489–495 (2006).