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Retrieval of microphysical characteristics of particles in atmospheres of distant comets from ground-based polarimetry

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ABSTRACT

We summarize unique aperture data on the degree of linear polarization observed for distant comets C/2010 S1, C/2010 R1, C/2011 KP36, C/2012 J1, C/2013 V4, and C/2014 A4 with heliocentric distances exceeding 3 AU. Observations have been carried out at the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (Nizhnij Arkhyz, Russia) during the period from 2011 to 2016. The measured negative polarization proves to be significantly larger in absolute value than what is typically observed for comets close to the Sun. We compare the new observational data with the results of numerical modeling performed with the *T*-matrix and superposition *T*-matrix methods. In our computer simulations, we assume the cometary coma to be an optically thin cloud containing particles in the form of spheroids, fractal aggregates composed of spherical monomers, and mixtures of spheroids and aggregate particles. We obtain a good semi-quantitative agreement between all polarimetric data for the observed distant comets and the results of numerical modeling for the following models of the cometary dust: (i) a mixture of submicrometer water-ice oblate spheroids with aggregates composed of submicrometer silicate monomers; and (ii) a mixture of submicrometer water-ice oblate spheroids and aggregates consisting of both silicate and organic monomers. The microphysical parameters of these models are presented and discussed.

1. Introduction

Physical properties of cometary atmospheres are known primarily on the basis of observational data obtained for bright comets close to the Earth and the Sun (mostly at 1–2 AU). It was believed early that the nature of the particles forming cometary comas does not depend on the heliocentric distance [1]. However, more recent observations show the existence of differences between the activity of close-to-the-Sun comets and those located at large heliocentric distances (see, e.g., Refs. [2–5]). Therefore, it is reasonable to expect that the nature of particles in these two types of comets may be different as well. Since polarimetric observations of comets often allow one to obtain useful information about the properties of particles in their comas, such measurements have been carried out intensively for comets close to the Sun (see Refs. [6,7] and references therein). However, no ground-based polarimetric observations had been performed until quite recently for distant comets (i.e., those at heliocentric distances exceeding 3 AU). The first results of such observations have been published in Refs. [8,9]. In particular, they show a deeper branch of negative polarization at small phase angles in comparison with that observed for comets close to the Sun. Despite the limited statistics of these observations, one can assume that the particulate compositions of the atmospheres of these two types of comets can also be different.

The investigation of optical properties of cometary particles based on the results of polarimetric observations carried out for bright comets has been a hot topic over the past 15 years (see, e.g., Refs. [10–19]). Nevertheless, even though observational data have been obtained over wide ranges of phase angles and wavelengths, there is still no definitive conclusion as to the nature, morphology, and size of the particles in the atmospheres of these comets. Typically, analyses of polarimetric observations are largely focused on the reproduction of the negative branch of linear polarization at small phase angles. As the initial step, a model of the particle morphology is selected, for example aggregates [10–14], agglomerated debris [16,17], spheroids [10,18], or a mixture of aggregates

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Table 1
Log of polarimetric observations of distant comets.

UT Date	r (AU)	Δ (AU)	α (deg)	Filter	λ_{eff} (μm)	T_{exp} (s)	P (%)	Object
Nov. 25.71, 2011	7.01	6.52	7.3	V	0.551	540	−1.9	C/2010 S1
Nov. 12.69, 2012	6.05	5.87	9.4	g-sdss	0.465	600	−2.01	C/2010 S1
Nov. 15.83, 2012	3.17	2.45	14.2	V	0.551	640	−2.0	C/2012 J1
Feb. 06.19, 2013	5.94	5.57	9.2	r-sdss	0.620	1260	−3.0	C/2010 R1
Nov. 05.89, 2015	4.21	3.28	4.9	r-sdss	0.620	450	−1.9	C/2014 A4
Nov. 06.15, 2015	5.19	4.61	9.4	R	0.642	450	−2.3	C/2013 V4
Nov. 25.82 2016	5.05	4.47	9.7	r-sdss	0.620	900	−2.5	C/2011 KP36

and spheroids [15,19]. In Ref. [8], the first attempt was made to analyze the results of polatimetric measurements obtained for the distant comet C/2010 S1. It was found that the model of dust in the form of compact aggregates of an overall radius $R_{ag} \sim 1.3\,\mu$m composed of $N = 1000$ spherical monomers with a radius $a = 0.1\,\mu$m and a refractive index $m = 1.65 + i0.05$ allows one to obtain a satisfactory agreement between the results of polarimetric observations and computations.

The new polarimetric observations of distant comets remain sparse and cannot be used yet to derive individual models of dust for each comet. However, their systematic deviation from the results of previous polarimetric observations of comets at small heliocentric distances undoubtedly warrants an initial theoretical analysis. Hence the main objectives of this paper are as follows: (i) to summarize recent polarimetric data observed for six distant comets; (ii) to present the results of theoretical modeling of light scattering characteristics performed for different particle morphologies and to compare them with the observations; and (iii) based on the results of this comparison, to discuss the possible composition of particles in the atmospheres of distant comets. The final section summarizes our findings.

2. Results of polarimetric observations

Table 1 summarizes the results of aperture polarimetric observations carried out for distant comets during the period from 2011 to 2016. These observations have been performed using the 6-m telescope of the Special Astrophysical Observatory (Nizhnij Arkhyz, Russia) with the multi-mode focal reducer SCORPIO-2 [20,21]. A detailed description of the procedure used to process polarimetric images is given in Refs. [9,22]. Table 1 provides the following information: the date of an observation (the mid-cycle time); the respective heliocentric, r, and geocentric, Δ, distances; the phase angle α; the spectral filter and its effective wavelength λ_{eff}; the total exposure time T_{exp}; the degree of linear polarization P; and the name of the comet. It should be noted that because the tabulated values of polarization have been obtained from measurements with a circular projected diameter of the aperture ranging from 5000 up to 8000 km, they only represent average values of polarization for a cometary coma. This is explained by the fact that active comets have extended atmospheres of varying structure [8]. As a consequence, the measured values of polarization depend on the aperture used, and hence allow one to infer only "average" characteristics of cometary particles.

In Fig. 1, we depict the observed values of the degree of linear polarization for short- and long-period close-to-the-Sun comets at phase angles $\alpha \le 25°$ and in the spectral interval 0.5–0.7 μm [23], as well as our observational data obtained for the distant comets C/2010 S1, C/2010 R1, C/2011 KP36, C/2012 J1, C/2013 V4, and C/2014 A4. It is obvious that in the range of phase angles considered, all the distant comets exhibit larger absolute values of negative polarization compared to those observed for comets at small heliocentric distances.

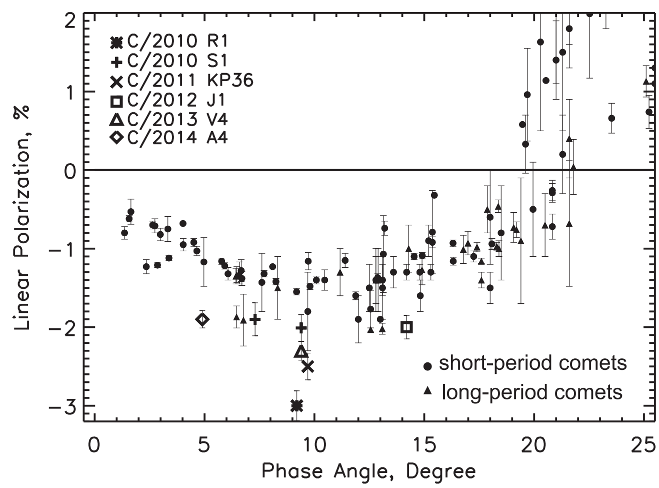

Fig. 1. Degree of linear polarization for comets at small heliocentric distances [23] and distant comets (this work).

3. Numerical modeling methodology

Theoretical modeling of the phenomenon of light scattering in the atmosphere of a comet is usually based on the assumption of a low volume concentration of the cometary particles. This assumption enables one to consider the cometary atmosphere as an optically thin cloud and thereby ignore the contribution of multiple scattering. For a macroscopically isotropic and mirror-symmetric particulate scattering medium, the far-field transformation of the Stokes parameters upon first-order scattering can be written in terms of the real-valued so-called normalized Stokes scattering matrix $\mathbf{F}(\theta)$:

$$\begin{bmatrix} I^{sca} \\ Q^{sca} \\ U^{sca} \\ V^{sca} \end{bmatrix} \propto \mathbf{F}(\theta) \begin{bmatrix} I^{inc} \\ Q^{inc} \\ U^{inc} \\ V^{inc} \end{bmatrix}$$

$$= \begin{bmatrix} F_{11}(\theta) & F_{21}(\theta) & 0 & 0 \\ F_{21}(\theta) & F_{22}(\theta) & 0 & 0 \\ 0 & 0 & F_{33}(\theta) & F_{34}(\theta) \\ 0 & 0 & -F_{34}(\theta) & F_{44}(\theta) \end{bmatrix} \begin{bmatrix} I^{inc} \\ Q^{inc} \\ U^{inc} \\ V^{inc} \end{bmatrix}, \qquad (1)$$

where $\theta \in [0°, 180°]$ is the angle between the incidence and scattering directions (i.e., $\theta = 180° - \alpha$, where α is the phase angle), and both sets of the Stokes parameters are defined with respect to the common scattering plane [24]. The element $F_{11}(\theta)$ is called the phase function and satisfies the normalization condition

$$\frac{1}{2}\int_0^{\pi} F_{11}(\theta)\sin\theta \mathrm{d}\theta = 1. \qquad (2)$$

If the incident light (in our case, sunlight) is unpolarized then the element $F_{11}(\theta)$ characterizes the angular distribution of the scattered intensity, while the ratio $-F_{21}(\theta)/F_{11}(\theta)$ represents the corresponding degree of linear polarization.