MODELLING OF POLARIZATION PROPERTIES OF COMETARY DUST GRAINS

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ABSTRACT

Observational data for dusty comets are summarized and systemized. The dependence of the linear polarization on various parameters (the phase angle, wavelength, etc.) is analyzed. An ensemble of aligned spheroidal particles having various sizes and chemical compositions is used to fit the linear and circular polarization observed for the comet Halley.

1. INTRODUCTION

Except for a few space missions to comets our information about cometary dust grains comes from the analysis of their electromagnetic radiation. Like atoms and molecules, dust particles have their own spectra. Most spectral features are located in the infrared (IR) wavelength range.

The optical properties of dust grains depend not only on their chemical composition but also on their size distribution, shape, the degree and direction of alignment. This creates additional difficulties in interpretation of observations of cometary dust.

The luminosity of comets is tightly connected with the solar radiation. Dust grains scatter or absorb it, the absorbed energy is reradiated in the IR wavelength range. Here, we paid our attention to the scattered part of the solar radiation.

The electromagnetic waves are characterized by their intensity and polarization. For atomic and molecular emissions the degree of linear polarization may be theoretically predicted (Le Borgne and Crovisier, 1987). For a dust grain of unknown shape and composition, the polarization may be additional diagnostic tool for their investigations.

Usually Mie theory for spherical particles is used for fitting the cometary observations. This contradicts with several direct indicators of a non-sphericity of cometary grains: for instance, non-zero degree of the linear polarization at the phase angle $\alpha^* = 0°$ (in this case the scattering angle $\Theta = 180° - \alpha^* = 180°$ and the Sun, the Earth and a comet are placed on one line).

In this paper, for the first time we interpret observations of the linear polarization for the comet Halley at different wavelengths using an ensemble of homogeneous oriented spheroids of various sizes, chemical compositions but a fixed shape. The degree of the circular polarization is also calculated.

2. OBSERVATIONAL DATA

2.1 Direct (in situ) measurements

The comet Halley was investigated by the Giotto and Vega 1, 2 spacecraftes. Chemical analysis of the cometary dust has shown that the grains mainly consist of silicates (chondrites) and carbonaceous materials. The dust experiments discovered the presence of both large and small particles in the cometary dust. We used the power law size distribution provided by the experiments

$$dn \sim r^{-2.5} dr, \tag{1}$$

where dn is the number of particles in the size range $[r, r + dr]$ (Mazets et al., 1986).

2.2 Polarimetric observations

The observed degree of the linear polarization is determined by the two processes: scattering of the solar radiation by cometary dust and resonance fluorescence of molecules

$$P = \frac{P^{\rm sca}_{\rm dust} F^{\rm sca}_{\rm dust} + P^{\rm em}_{\rm mol} F^{\rm em}_{\rm mol}}{F^{\rm sca}_{\rm dust} + F^{\rm em}_{\rm mol}}, \tag{2}$$

where $P^{\rm sca}_{\rm dust}$, $F^{\rm sca}_{\rm dust}$, $P^{\rm em}_{\rm mol}$, $F^{\rm em}_{\rm mol}$ are the degree of polarization and flux of the dust and gaseous components, respectively. In Eq. (2)

$$P = P(\alpha^*, \lambda, D, r_{\rm H}), \tag{3}$$

where α^* is the phase angle, λ the wavelength, D the aperture, $r_{\rm H}$ is the heliocentric distance of a comet.

The phase dependence of the polarization shows features common to all comets: it has negative branch at $\alpha^* < 20°$, changes the sign at phase angle $\sim 20°$ (the inversion angle α^*_0) and reaches the maximum around 90° (see Fig. 1 in Jockers, 1998). The maximum degree of polarization is about 25%–30% for the dusty comets and 8%–15% for the gaseous ones.

The dusty comets are characterized by strong continuum, weak gas emissions and a high dust-to-gas ratio. The phase curves for these comets are similiar within the accuracy of observations. Before the appearance of the comet Hale-Bopp, the dusty comets were believed to follow a common phase curve of polarization. The group of the dusty comets includes the comets: 1P/Halley, C/Hale-Bopp (1995 O1), C/Hyakutake (1996 B2), etc. The phase curve of polarization observed for the comet Halley is typical of the comets of this type (see Figs. 1–3).

The gaseous comets have weak continuum, numerous emission lines observed almost everywhere in the visible spectrum and a low dust-to-gas ratio. The group of the gaseous comets includes the comets: P/Austin (1982 VI), Kobayashi-Berger-Milon (1975 IX), Tabur (1996 Q1), etc.

The degree of polarization grows with an increase of the wavelength from the visual to IR. The main observed parameters describing the polarization of the comet Halley are presented in Table 1.

Table 1: Parameters of the phase curve for the comet Halley at different wavelengths. Errors are about $0.5°$ for the angles and 0.25% for the polarization degree

λ	α_0^*	$\alpha_{\min}^*$	$P_{\min}$	$P_{\max}$	$\frac{dP}{d\alpha^*}\mid_{\alpha_0^*}$
3650Å	$17°.0$	?	?	15.5%	?
4840	20.5	$10°.0$	-1.3%	16.9	$0.20\%/1°$
6700	23.5	10.5	-1.5	17.1	$0.25\%/1°$

We used the observational data from the following papers: the degree of polarization from Kikuchi et al. (1987), the positional angle of polarization and circular polarization from Dollfus and Suchail (1987).

Data obtained with approximately equal projected area of the aperture centered on the nucleus of the comet were utilized. This allows us to exclude the influence of variations of the degree and direction of polarization observed in outer parts of coma.

The dependence of the degree of the linear polarization from the heliocentric distance of a comet is masked by phase angle variations. For group of dusty comets the degree of the linear polarization is similiar at the same phase angles while their heliocentric distances can be different. Apparently, available observations do not allow us to study this effect.

The observations of circular polarizations of comets are very hard to do, so they can be done only episodically. The comet Halley is an exception: the observational data are availible for various phase angles.

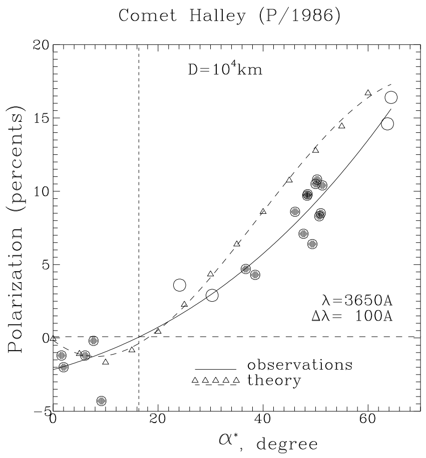

Figure 1: Degree of the linear polarization as a function of the phase angle α^* for $\lambda = 3650$Å. All error bars usually are less than size of signs

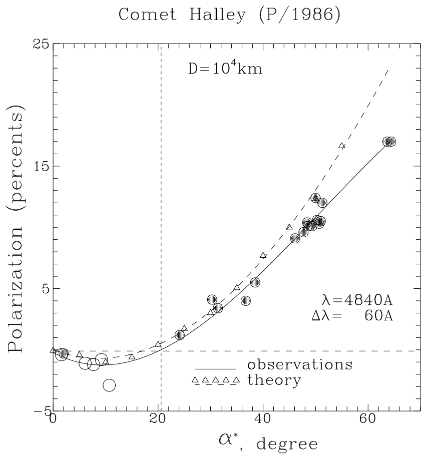

Figure 2: The same as Fig. 1 but for $\lambda = 4845$Å

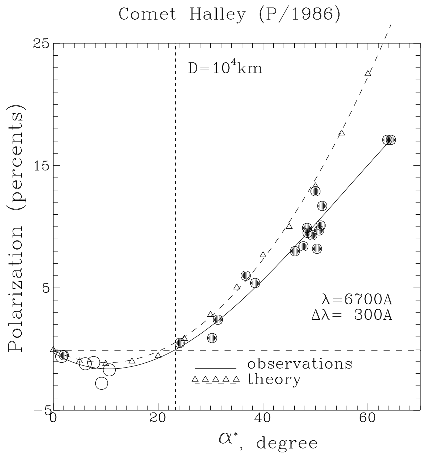

Figure 3: The same as Fig. 1 but for $\lambda = 6700$Å

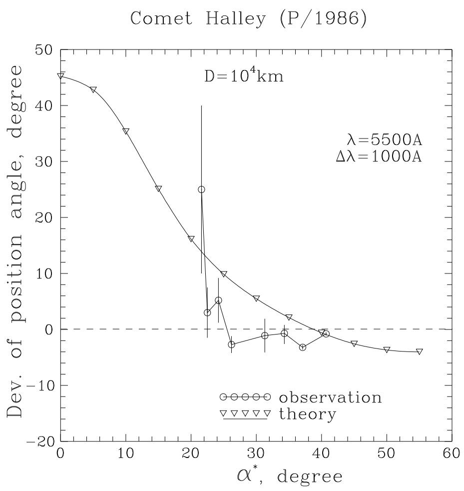

Figure 4: Deviations of the position angle of the linear polarization as a function of the phase angle α^*

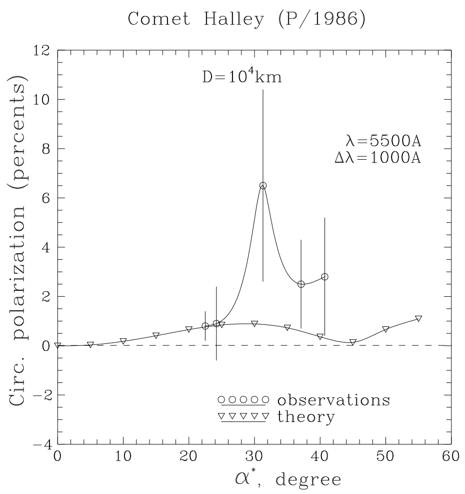

Figure 5: Degree of the circular polarization as a function of the phase angle α^*. All error bars are presented by vertical lines

2.3 Non-spherical particles in comets

Single light scattering by the oriented non-spherical particles produces phenomena which cannot be explained using the spherical particles, namely:

1. the non-zero circular polarization (Metz and Haefner, 1987);
2. rotation of the position angle with time, wavelength and in different parts of a comet (Dollfus and Suchail, 1987);
3. non-zero degree of the linear polarization at the phase angle $\alpha^* = 0°$;
4. non-zero degree of the linear polarization of stellar radiation observed during stellar occultations by a comet (Rosenbush et al., 1994).

3. MODEL

For calculations we used the numerical code based on the exact solution to the light scattering problem by the Separation of Variable Method (Voshchinnikov and Farafonov, 1993). The algorithm of calculations was as follows:

1. calculation of an array of scattering matrices;
2. the averaging over rotation;
3. the averaging over a size distribution function;
4. mixing of scattering matrices for different materials;
5. calculations of Stokes parameters and a comparison with observations.

Relative errors of the calculations were usually less than 0.1%.

The best model found has the following parameters:
- mixture of 80% astronomical silicate (astrosil) and 20% amorphous carbon (AC1);
- prolate (50%) and oblate (50%) spheroids;
- aspect ratio $a/b = 2.0$;
- $r_{\rm V} = 0.05 - 0.25\,\mu$m for AC1;[1]
- $r_{\rm V} = 0.05 - 0.55\,\mu$m for astrosil;
- $\gamma = -2.5$;
- $\Omega = 75°$;[2]
- perfect rotational (Davies-Greenstein, DG) orientation.

The value of γ and the chemical composition of grains were chosen on the basis of direct (in situ) measurements and ground-based observations. Other parameters were estimated by fitting the observed quantaties.

4. COMPARISON WITH OBSERVATIONS

The observed and calculated curves are plotted in Figs. 1–5. A good agreement with the observations is only for the negative branch of the polarization curve, when $\alpha^* < 30°$ (Figs. 1–3). The degree of the calculated polarization is higher than observed at $\alpha^* > 40° - 50°$ that is connected with the high polarization efficiency of the small amorphous carbon grains at these phase angles.

[1] $r_{\rm V}$ is the radius of the sphere whose volume is equal to that of a spheroid.
[2] Ω is the angle between alignment direction and direction of light propagation.

Deviations of the position angle of the linear polarization plotted in Fig. 4 show that the model satisfactorily explains the observations. The same can be said about the behaviour of the circular polarization presented in Fig. 5. A better agreement between the theory and observations of the circular polarization may be reached if one decreases the fraction of astrosil in the model.

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