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# Polarimetric properties of asteroids

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**Abstract**

Quite frequently astronomic polarimetric observations of different celestial bodies do not guarantee a proper phase angle coverage that is required for estimating all of the attributes of their polarization phase curves with a high accuracy. To approximate the phase dependences of polarization observed for particulate surfaces, we use a simple empiric formula recently suggested by Shestopalov (2004). The efficiency of the approximating function in a wide range of phase angles is illustrated with the use of the results of polarimetric measurements of lunar areas, lunar samples, and near-Earth asteroids. For asteroids of various types, we can reproduce their negative polarization branches with adequate accuracy and roughly estimate a probable value of the maximum polarization degree at an appropriate phase angle. From the polarimetric database available at NASA PDS [Asteroid Polarimetric Database V7.0 (2012)] we calculated the main parameters of 153 polarimetric curves of asteroids in various spectral bands with the accuracy comparable to the observation errors. One more purpose of our analysis was to find correlations between the polarimetric and photometric properties of asteroids. For C-, M-, S-, E-type asteroids, the characteristics of the negative branch of polarization curves turned out to correlate closely with the phase coefficient of the photometric function of asteroids and the photometric roughness of asteroid surfaces. This implies that the complex geometry of the surface microrelief affects the polarization properties of asteroids. In particular, the data scattering around regression lines on the plots of the albedo versus the depth of negative polarization branch and the slope of the polarimetric function at inversion angle strongly depends on the differences in the photometric roughness of asteroid surfaces.


*Keywords:* Minor planets; Asteroids; Polarization phase curves; Albedo; Surface roughness

## 1. Introduction

Initially unpolarized solar light being scattered from a rough surface of atmosphereless celestial bodies is partially linearly polarized. The plane of polarization is either normal to the plane containing the incident and reflected rays (the so-called scattering plane) or parallel to it. In planetary sciences the degree of linear polarization is usually described as $P_r = (I_\perp - I_\parallel)/(I_\perp + I_\parallel)$, where the intensities $I_\perp$ and $I_\parallel$ are the polarized components of the scattered radiation in the planes normal and parallel to the scattering one, respectively. The linear polarization degree is a function of the phase angle, $\alpha$, which is bounded by the incident and observation directions. For the most atmosphereless bodies, $I_\parallel > I_\perp$ at the phase angles less than ~30°, i.e., the polarization degree is negative in accordance with the above definition. The negative polarization branch is commonly defined by the following parameters: the maximum degree of negative polarization (in absolute units) $P_{min}$ at the corresponding phase angle $\alpha_{min}$; the inversion angle $\alpha_i$, i.e. the phase angle, where the polarization degree changes sign from negative to positive, when moving from opposition; the polarimetric slope $h = dP/d\alpha$ at $\alpha = \alpha_i$. At phase angles larger than $\alpha_i$, the positive polarization degree reaches its maximum, $P_{max}$, at the phase angle $\alpha_{max}$ and

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tends again to zero, when the phase angle $\alpha$ approaches 180°. A plot of the polarization degree versus the phase angle gives a curve characteristic of the surface studied.

Due to the specificity of astronomical observations, usually the resulting dataset does not allow determining all the features of a phase curve of polarization with a reasonable accuracy. Therefore, one of the aspects of polarimetric investigations is to find an empiric formula for approximating as accurately as possible the polarimetric phase curves of the studied objects. This analytic expression should be easily used and predict with a reasonable accuracy such polarimetric parameters as $P_{max}$ and $\alpha_{max}$ that cannot be measured from the Earth. The shape of the phase polarimetric function of a rough surface is more complicated than that of the phase photometric function, so that only several empiric formulae for the phase dependence of polarization are presently known.

Seemingly, Lumme and Muinonen (1993) were the first, who set the above task. The authors offered a four-parameter empiric trigonometric function for calculating the polarimetric curves of celestial bodies,

$$P(\alpha) = b\sin^{c1}(\alpha) \times \cos^{c2}(\alpha/2) \times \sin((\alpha - \alpha_i)/2) \qquad (1)$$

which was used in the analysis of polarization phase curves of asteroids and comets (e.g., Goidet-Devel et al. (1995) and Penttilä et al. (2005)). The free parameters, adjustable while running, are $b$, $c1$, $c2$, and the inversion angle $\alpha_i$. The phase angle varies from 0 to 180°.

In their polarimetric investigations of asteroids and comets, Cellino et al. (2010) applied the following three-parameter formula that had been firstly proposed by Piironen et al. (2000):

$$P(\alpha) = A_0(\exp(-\alpha/A_1) - 1) + A_2\alpha \qquad (2)$$

where the $A_0$, $A_1$, and $A_2$ are free parameters adjustable in the range of small phase angles (<30°).

For the joint analysis of polarimetric and photometric properties of asteroids, Muinonen et al. (2002) offered and then applied (Muinonen et al., 2009) a four-parameter empiric linear-exponential formula:

$$f(\alpha) = ae^{-\alpha/d} + b + k\alpha \qquad (3)$$

Here the $a$, $d$, $b$, and $k$ are adjustable parameters, and $0 \leqslant \alpha < 30°$. This expression was successfully used by several researchers (e.g., Kaasalainen et al. (2001, 2003)) to approximate the polarization phase curves of asteroids and other Solar System objects.

In his turn, Shestopalov (2004) approximated the polarization phase curves of asteroids by a five-parameter empirical formula:

$$P(\alpha) = B(1 - e^{-m\alpha})(1 - e^{-n(\alpha-\alpha_i)})(1 - e^{-l(\alpha-\pi)}) \qquad (4)$$

where a scaling factor $B$ is expressed in terms of the slope $h$ of the polarization curve at the inversion angle $\alpha_i$, namely

$$B = \frac{h}{n(1 - e^{-m\alpha_i})(1 - e^{-l(\alpha_i-\pi)})}.$$

The phase angle $\alpha$ varies in the range of 0–180°, and the $m$, $n$, $l$, $h$, and $\alpha_i$ are free parameters.

So, Eqs. (1) and (4) can approximate the phase-dependent polarization data for rough surfaces in the phase-angle range from zero and the angle of the polarization maximum, $\alpha_{max}$. However, as we have repeatedly ascertained by routine tests, Eq. (1) loses in accuracy as compared to Eq. (4) in the fitting process for asteroids (especially, the asymmetric negative branches) and for lunar areas (especially in the range of the polarization maximum). Note also that Eq. (4), in contrast to Eq. (1), successfully approximates the "unusual" polarimetric curves of terrestrial samples measured in laboratory (see Fig. 1 in Shestopalov, 2004).

Piironen's formula, Eq. (2), fits well the measured phase curves of polarization of asteroid surfaces in the range of small phase angles (~30° and less), but yields the linear approximation for *any* phase angles at very small values of the $1/A_1$ parameter (i.e., $P(\alpha) \approx \alpha_0 \times (-\alpha/A_1) + A_2\alpha$ if $1/A_1 << 1$). In turn, Eq. (4) leads to a quadratic equation provided that parameters $m$, $n$, $l << 1$ and $0 < \alpha$, $\alpha_i << \pi$, that is

$$P(\alpha) = \frac{h}{\alpha_i}\alpha(\alpha - \alpha_i).$$

This expression no longer depends on $m$, $n$, and $l$ parameters and yields the simplest relations between the parameters of the negative polarization branch: $4|P_{min}|/h = \alpha_i = 2\alpha_{min}$. It is interesting that, in the range of small phase angles, several low-albedo asteroids have the phase dependences of polarization that are a very close to the above quadratic equation.

In fact, Eq. (2) is a particular case of Eq. (3) when $b = -a$. In turn, Eq. (3) is the particular case of Eq. (4) when $0 < n$, $l << 1$ and $0 < \alpha$, $\alpha_i << \pi$. Besides, the $a$, $b$, $k$ and $d$ parameters are expressed in terms of the $m$, $h$, and $\alpha_i$ parameters of Eq. (4); thus, the formula in question contains three, but not four parameters. In other words, Eq. (3) provides the same accuracy as Eq. (4) in the calculations of polarimetric curves in the range of small phase angles, but fails to reproduce the polarization maximum $P_{max}$ at a proper angle $\alpha_{max}$.

To approximate the measured phase dependences of polarization of asteroids, some researchers prefer the least squared fitting by third-degree polynomials (e.g., Goidet-Devel et al., 1995 and references therein). However, the $n$-degree polynomials are resulted from the series expansion of the exponents entering in Eq. (4), so that any of the polynomials is only a particular case of Eq. (4). We have repeatedly made sure that the curve fitting by Eq. (4) provides a higher accuracy than the polynomial approximation does. Besides, the regression equations work in their domain of definition and often lead to large errors, when an argument is outside the definition domain.

So, Eq. (4) has obvious advantages over Eqs. (1)–(3) that were applied in the previous studies referred above. In the next section of the paper, the effectiveness of