SOME NEW ASPECTS IN ANALYZING PHOTOPOLARIMETRIC OBSERVATIONS OF PLANETS

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Some new difficulties appearing in analyzing polarimetric observations of planets with optically thick and optically thin atmospheres are discussed. Using the atmosphere of Jupiter as an example, it is demonstrated that specific choice of particle shape in model computations can affect significantly the values of cloud particle parameters retrieved from photopolarimetric data. Besides, we consider the influence of various factors on the interpretation of ptotopolarimetric observations of Mars performed during periods of high transparency of its atmosphere. The re-analysis of the polarization phase curves obtained in such periods shows the impossibility to derive reliable estimates of the properties of Martian dust particles.

INTRODUCTION

Planetary polarimetry reached new heights in the 1960s–1970s when modern photopolarimeters were used in the ground-based and space observations. At the same time various methods for computing multiple scattering in thick atmospheres were developed also. Then, a large number of measurements of the intensity and degree of linear polarization of sunlight reflected by the atmospheres of Venus, Mars, Jupiter, and Saturn have been carried out. The interest in such studies stems from the fact that polarization of light scattered by a planetary atmosphere is very sensitive to microphysical properties of atmospheric aerosols such as their size and refractive index. The pioneers in this field were Coffeen [2], Hansen and Arking [7], and Hansen and Hovenier [8], who studied the Venusian atmosphere. Afterwards, detailed remote-sensing analyses were carried out for the atmospheres of Jupiter, Saturn and Mars during the periods of clear atmosphere and the dust storm of 1971 [1, 6, 9, 12], and as a result for a model of planetary cloud layer consisting of **spherical** particles the values of refractive index, mean radius, and size distribution function were derived. In this presentation we consider some new aspects appeared in analyzing photopolarimetric observations of planetary atmospheres. This work is based on the results obtained by Dlugach, Mishchenko [4], and Dlugach, Petrova [5].

I. OPTICALLY THICK CLOUD LAYER OF JUPITER

Cloud particles in the atmospheres of Jupiter and Saturn and dust particles in the Martian atmosphere are likely nonspherical. This brings up the important questions: how strong can the effect of nonsphericity be on the accuracy of remote-sensing retrievals, and to what extent can the model of spherical particles be used in calculations of scattering properties of nonspherical aerosols. Therefore, one of the purposes of this presentation is to clarify just this issue by using the example of the Jovian atmosphere.

A detailed analysis of ground-based observations of Jupiter using the model of spherical cloud particles with full account of polarization was performed previously by Mishchenko [9]. Then, spectropolarimetric data for the center of the Jovian disc collected by Morozhenko [11] at wavelengths $\lambda = 0.423$, 0.452, 0.504, 0.600, and 0.798 μm in the phase angle range $0^\circ < \alpha < 11^\circ$ and the spectrophotometric data by Woodman *et al.* [13] obtained in the wavelength range from 0.300 to 1.076 μm at the phase angle $\alpha = 2^\circ$ were used. As a result, for gamma-size distribution, good agreement between the observational data and model computations was found for the model of semi-infinite cloud layer with the values of the real part of the refractive index m_R, the effective radius r_{eff}, and the effective variance v_{eff} which are presented in the first line of Table 1.

In order to clarify the influence of the particle shape, we have chosen randomly oriented oblate and prolate spheroids and finite circular cylinders to model the likely nonsphericity of the Jovian tropospheric aerosols.

The shape of such particles is fully described by just one parameter, *i.e.,* axial ratio E (the ratio a/b of the horizontal axis to rotational one for spheroids and the diameter-to-length ratio D/L for cylinders). Using T-matrix and vector radiative-transfer codes, together with the values of the microphysical parameters listed in the first line of Table 1, we carried out computations of the phase dependence of the degree of linear polarization for the radiation reflected by the planetary disc center. The calculations were performed for two values of the axial ratio $E = 1.5$ (oblate particles) and $E = 1/1.5 = 0.666...$ (prolate particles). The corresponding results are depicted in Fig. 1. It can be seen that the results of computations for all the models of nonspherical particles differ substantially from the observational data as well as from the results obtained for spheres. To learn more about the effect of nonsphericity, we also performed computations for oblate spheroids with $E = 1.3$. As could have been expected, in this case the agreement with the observation results and with the calculations for spheres is noticeably better. Thus, we can conclude that the specific choice of aerosol shape model affects significantly the results of retrievals of particle microphysical characteristics from polarimetric measurements. As a consequence, the model parameter values derived for spherical aerosol can be expected to be inadequate if the clouds in the Jovian atmosphere consist largely of nonspherical particles.

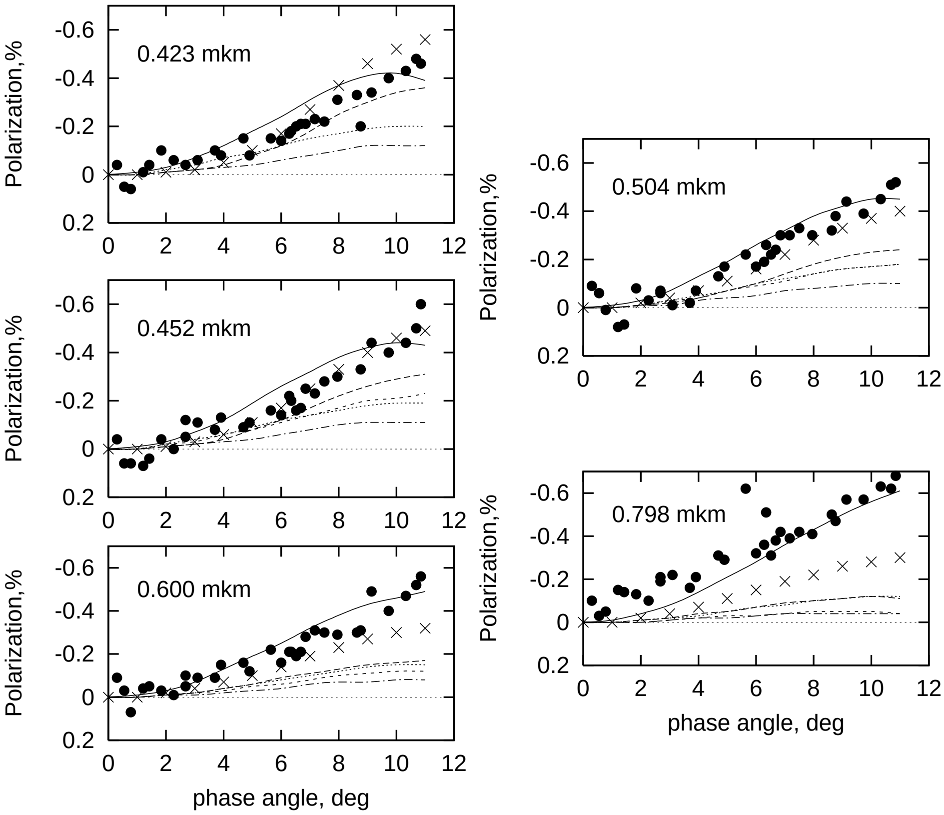

Figure 1. Phase-angle dependence of the degree of linear polarization for the Jovian disc center. The dots show the observation results by Morozhenko [11]. The curves and crosses are the results of model computations for the model A atmosphere and various cloud-particle shapes with $m_R = 1.386$, $r_{\text{eff}} = 0.385$ μm, and $v_{\text{eff}} = 0.45$, as follows. Solid curves: spheres; long-dashed curves: oblate spheroids with $a/b = 1.5$; dotted curves: oblate cylinders with $D/L = 1.5$; dot-dashed curves: prolate spheroids with $a/b = 1/1.5$; short-dashed curves: prolate cylinders with $D/L = 1/1.5$; crosses: oblate spheroids with $a/b = 1.3$

As the next step in our analysis, we attempted to quantify the effect of particle shape on the retrieved values of refractive index and size distribution. For this purpose, we performed computations for oblate and prolate, randomly oriented, polydisperse spheroids and cylinders with axial ratios $E = 1.3$, 1.5, 1/1.3, and 1/1.5 and for various values of m_R, m_I, r_{eff}, and v_{eff}. We adopted simple radiative-transfer models to describe the upper Jovian atmosphere: A) a semi-infinite homogeneous layer composed of uniformly mixed gas and cloud particles, and B) a two-layer atmosphere in which a gas layer of optical thickness τ_g overlays a semi-infinite homogeneous layer composed of a uniform mixture of gas and cloud particles.

As a result, we found that a model B atmosphere with the optical thickness of the top gaseous layer $\tau_g = 0.2$

Table 1. Best-fit microphysical parameter values for spheres and various nonspherical particle models

Shape	E	m_R	$r_{\rm eff}$, μm	$v_{\rm eff}$	Model
Spheres	1.0	1.386	0.385	$0.4 \div 0.5$	A
Spheroids	1.3	1.45	0.35	0.40	B
Spheroids	1.5	1.52	0.40	0.35	B
Spheroids	1/1.3	1.50	0.35	0.30	B
Spheroids	1/1.5	1.54	0.90	0.30	A
Cylinders	1.3	1.43	0.47	0.40	B
Cylinders	1/1.3	1.49	0.60	0.40	B

at $\lambda = 0.423$ μm (and appropriate values at the other wavelengths consistent with the spectral behaviour of the Rayleigh extinction) can reproduce the polarimetric data quite well provided that the cloud particles are spheroids with $E = 1.3$, 1.5, 1/1.3 and cylinders with E =1.3, 1/1.3. Similar computations for model A atmospheres were found to fit the observational data provided that the cloud particles are prolate spheroids with $E = 1/1.5$. The resulting best-fit values of m_R, $r_{\rm eff}$, and $v_{\rm eff}$ are listed in Table 1. As an example, in Figs. 2 and 3 we show the corresponding polarization phase curves computed for oblate and prolate spheroids with E =1.5 and E =1/1.5.

I. CONCLUSION

Thus, the results of our calculations show that:

– Even weak asphericity of the assumed particle shape causes significant changes in the values of the particle microphysical characteristics as compared with those derived using the model of spheres. In the cases considered, the real part of the refractive index increases quite significantly with increasing particle asphericity. The retrieved value of the effective radius can also change by a factor exceeding 2 depending on the assumed particle shape.

– The lack of a priori information on the actual particle shape limits our ability to obtain reliable estimates of other particle microphysical parameters based on analyses of polarimetric measurements taken at a narrow range of phase angles.

– The availability of observational data at a wider range of phase angles can provide additional constraints on the aerosol shape and make the inverse remote-sensing problem less ill-posed.

II. OPTICALLY THIN CLEAR ATMOSPHERE OF MARS

The problem to interpret polarimetric observations of Mars during the periods of high transparency of its atmosphere is still more complicated as compared with analyzing observational data obtained for planets with optically thick cloud layers. Along with difficulties appearing for optically thick atmospheres, mentioned above, in this case it is also necessary to take into account the contribution of surface. We would recall that Morozhenko [10] attempted to derive the parameters of the optically thin Martian atmosphere using the polarimetric observational data in the spectral region of 0.225 to 0.434 μm for a phase angle of 25.4°. In this analysis it was assumed that the position of the polarization inversion angle for the Martian surface did not depend on wavelength in the ultraviolet too, and is situated at 25.4°. As a result, there were found the values of the real part of the refractive index m_R, the geometric mean of the radii r_0 for the log-normal particle size distribution with dispersion $\sigma^2 = 0.1$ which are given in the last column of Table 2. Obtained estimate of the refractive index spoke in favour of silicate nature of aerosol. But, the values of mean radius and optical thickness of the dust layer turned out to be much less than the corresponding estimates found by other authors from analyzing the data of some space experiments. Therefore, we decided to revisit this problem for clarifying the cause of this disagreement although such attempts had been already done before. In particular, in the work of Dlugach, Mishchenko, and Morozhenko [3] it was obtained that the values of r_0 and τ_a^0 for dust spheroidal particles with $E = 2.0$ proved to be nearly twice as large as those of spheres. However, they are still much less than the available estimates derived, in particular, from space experiments.

Using the same model, the same observational data and the same technique, we obtained that the values of m_R, r_0 and τ_a^0 listed in Table 2 give a good agreement between calculations and measurements within the same accuracy as those found in [10]. Besides, for other values of refractive index (out of the interval from 1.3 to 1.6)

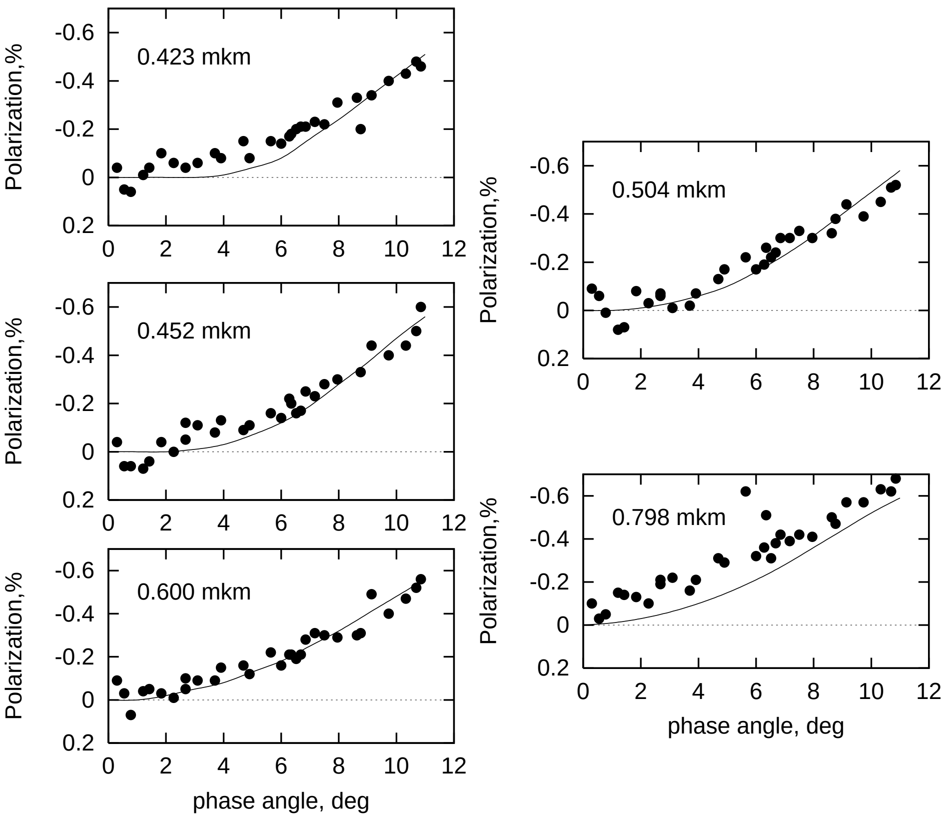

Figure 2. Same as in Fig. 1, but for oblate spheroids with $a/b = 1.5$, $m_R = 1.52$, $r_{\rm eff} = 0.40$ μm, and $v_{\rm eff} = 0.35$ (model B)

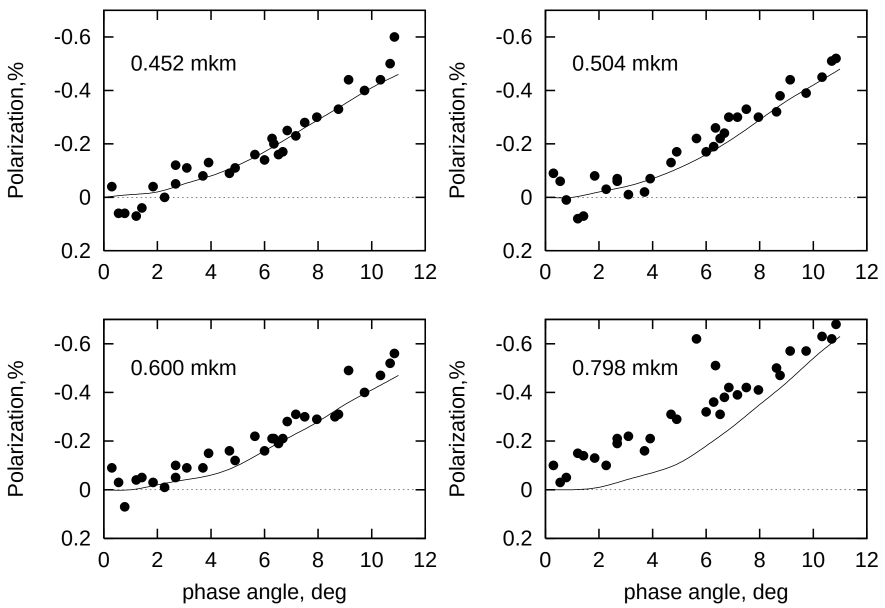

Figure 3. Same as in Fig. 1, but for prolate spheroids with $a/b = 1/1.5$, $m_R = 1.54$, $r_{\rm eff} = 0.90$ μm, and $v_{\rm eff} = 0.30$ (model A)

Table 2. Optical properties of the Martian atmosphere composed of spherical particles with various refractive indexes

m_R	1.31	1.35	1.39	1.45	1.48	1.5–1.6
r_0, μm	0.065	0.060	0.060	0.055	0.050	0.051–0.047
$\tau_a^0(0.225\ \mu\text{m})$	0.120	0.098	0.098	0.080	0.080	0.076–0.065

one can also find such values of r_0 and τ_a^0 that provide a good agreement between the calculated and measured values of polarization at a phase angle of 25.4° within the same accuracy.

Figure 4 presents the measurement data (points) and calculation results for $m_R = 1.31$, $r_0 = 0.065\ \mu$m (solid curves) and $m_R = 1.5$, $r_0 = 0.05\ \mu$m (dashed curves). It is seen that the polarization phase curves calculated for both refractive indexes practically coincide. This can be explained as follows. For small phase angles, which are available for ground-based observations of Mars, the second element of the scattering matrix, appearing in calculations of the linear polarization, depends very weakly on both the refractive index and the shape of aerosol if the particles are very small. Consequently, small variations in the radius and aerosol content give possibility to obtain a good agreement between the calculations and measurements for particles of various shapes (for example, spheres and spheroids) in a very wide interval of the refractive index.

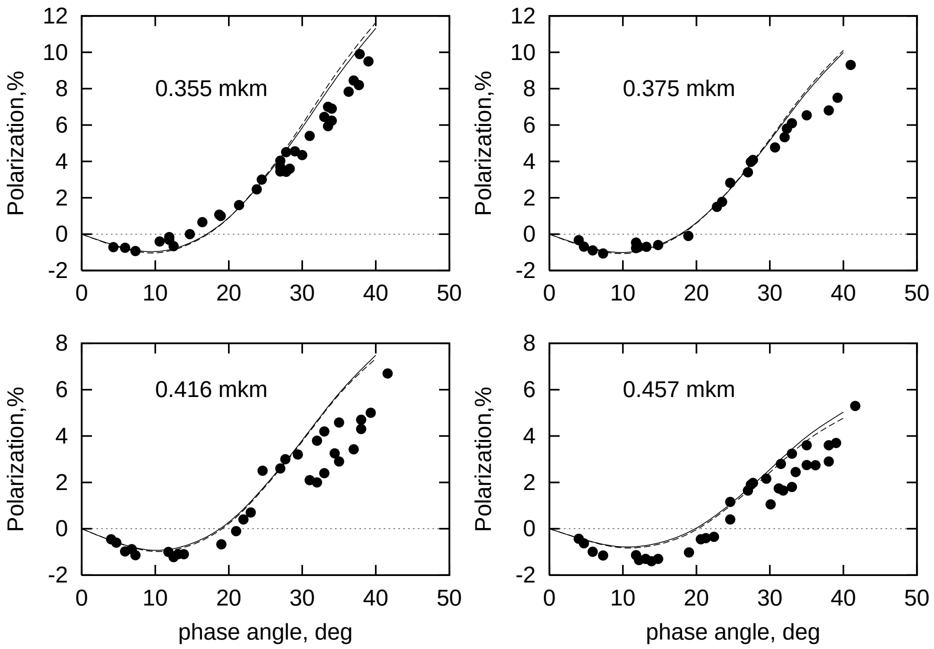

Figure 4. The polarization phase curves of Mars in periods of high atmospheric transparency for several wavelengths. The measurement data are shown by points. Solid curves: calculation results for $m_R = 1.31$, r_0 =0.065 μm; dashed curves: calculation results for m_R =1.5, $r_0 = 0.05\ \mu$m

II. CONCLUSION

The analysis of polarimetric observational data performed in [10] does not allow deriving the nature of aerosol in the Martian atmosphere during the periods of high transparency. In our opinion, it may be caused by some reasons. In particular:

- There are no reliable data concerning the position of the polarization inversion point in the blue and ultraviolet.
- The contribution of dust aerosols and ice clouds and hazes can not be distinguished from the integral ground-based polarimetric observations of Mars under high atmospheric transparency of its atmosphere.

– The limitation to the ultraviolet spectral range could lead to “washing” the information of large particles, which can exist in the lower atmospheric layers and become apparent in the data obtained at longer wavelengths.

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