Spectropolarimetry of planets: what observational data can be essential for correct microphysical retrievals of atmospheric aerosols

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Abstract

We present the results of computations of the degree of linear polarization for the center of a planetary disk in the phase angle range 0°< α < 90°. The computations were performed for various models of the cloud layer of Jupiter derived in [1–3] on the basis of spectropolarimetric observations of Jupiter [4]. For $\alpha \geq 15°$, our results show a noticeable difference in the value of polarization depending on the adopted cloud-particle model. We conclude that the availability of observational data in a wide range of phase angles can provide critical constraints on the particle shape.

1 Introduction

In our previous publications [2, 3], we have used Jupiter as a "testing ground" and have demonstrated that the optical properties of cloud particles (especially the refractive index) cannot be reliably estimated on the basis of measurements performed in a narrow range of phase angles. Using the results of ground–based spectropolarimetric observations of the center of the Jovian disk [4], we found that the assumed shape of atmospheric aerosols is essential in estimating their microphysical properties. Specifically, varying the assumed particle shape resulted in significant changes in the retrieved refractive index, size, and atmospheric structure. In this paper, we analyze how an extension of the phase angle range can help in the determination of the particle shape and, as a consequence, yield more accurate retrievals of the optical properties of cloud particles.

2 Atmosphere models and computational techniques

A detailed analysis of ground-based observation of Jupiter, using the model of a cloud layer composed of spherical cloud particles was performed in [1]. Subsequently, the case of nonspherical particles was considered in [2, 3]. In all three publications, we used spectropolarimetric data for the center of the Jovian disk collected by Morozhenko [4] at wavelengths λ = 0.423, 0.452 0.504, 0.600, and 0.798 μm in the phase angle range 0° < α < 11°. Two models of the Jovian atmosphere were considered: (A) a homogeneous semi-infinite layer composed of gas and cloud particles; and (B) a two-layered medium with a layer of pure gas of optical thickness τ_0 on top of a semi-infinite homogeneous layer composed of gas and cloud particles. The semi-infinite homogeneous layer was supposed to consist of spheres, randomly oriented oblate or prolate spheroids, or randomly oriented cylinders with varying aspect ratios *E*. Particle polydispersity was characterized by a simple gamma size distribution. As a result, a good agreement between the observational data and the model results was found for the values of the real part of the refractive index m_R, the effective radius r_{eff}, the effective variance v_{eff}, and the model of atmosphere listed in Table 1.

Table 1. Best-fit microphysical parameter values for various particle models, derived in [1–3]

Shape	E	m_R	r_{eff}, μm	v_{eff}	Model
Spheres	1.0	1.386	0.385	0.45	A
Oblate spheroids	1.3	1.45	0.35	0.40	B
Oblate spheroids	1.5	1.52	0.40	0.35	B
Prolate .spheroids	1.3	1.50	0.35	0.30	B
Prolate spheroids	1.5	1.54	0.90	0.30	A
Oblate cylinders	1.3	1.43	0.47	0.40	B
Prolate cylinders	1.3	1.49	0.60	0.40	B

To interpret polarimetric data for the center of a planetary disk, it is necessary to calculate the degree of linear polarization $P = -Q/I$. The first two components, I and Q, of the Stokes vector **I** of the reflected radiation are given by

$$I(-\mu, \varphi) = \mu_0 R_{11}(\mu, \mu_0, \varphi - \varphi_0), \tag{1}$$

$$Q(-\mu, \varphi) = \mu_0 R_{21}(\mu, \mu_0, \varphi - \varphi_0), \tag{2}$$

where (μ_0, φ_0) and ($-\mu$, φ) specify the directions of light incidence and reflection, respectively, and R_{11} and R_{21} are elements of the 4×4 Stokes diffuse reflection matrix **R**. In our computations, we first used the T-matrix approach to determine the elements of the single-scattering matrix **F** [5]. Then the elements R_{11} and R_{21} for model A were computed by means of a numerical solution of the Ambartsumian's nonlinear integral equation [6]. The overlaying gas layer in model B was incorporated by means of a computational algorithm based on the invariant imbedding technique as described in [7].

3 Results of computations and discussion

We performed calculations of the degree of linear polarization for the center of a planetary disk ($\mu_0 = \cos\alpha$, $\mu = 1$) for the range of phase angles $0° \le \alpha \le 90°$, spectral interval of $\lambda = 0.423 \div 0.798$ μm, and the models of cloud particles listed in the Table 1. The results of the computations are shown in Figs. 1 and 2. Figure 1 depicts the calculated phase-angle dependences of the degree of linear polarization for $0° \le \alpha \le 30°$ (left-hand column), $30° \le \alpha \le 60°$ (middle column), and $60° \le \alpha \le 90°$ (right-hand column). For $\alpha > 15°$ and all wavelengths, one can see a significant difference in the behavior of the polarization curves depending on the adopted cloud-particle model. For instance, in the wavelength range $0.423 \div 0.504$ μm in the case of spheres, the negative polarization has a minimum absolute value (compared to the cases of other particle shapes), and the sign of polarization changes twice (at $\alpha \approx 15$–20 and 30°). For longer wavelengths, the sign of polarization changes once at $\alpha \approx 25°$, and then the magnitude of the positive polarization increases with increasing phase angle. In the case of prolate spheroids with $E = 1.5$, for $\lambda = 0.423 \div 0.504$ μm the behavior of polarization is somewhat similar to that in the case of spheres, but in a longer wavelength range polarization is always negative. For other particle shapes, one can see that the absolute value of the negative polarization first increases with increasing phase angle, reaches its maximum value, and then starts to decrease. At some value of phase angle, the polarization becomes positive and increases with increasing phase angle. However, for different particle shapes we see a noticeable difference in the position of minumum of the negative polarization and the polarization inversion point, as well as in values of polarization. It is possible that such different behavior of polarization at the center of a disk for $\alpha > 15°$ is caused by a specific behavior of the single-scattering matrix element F_{12}. To confirm this supposition, we include Fig. 2 which depicts the calculated dependences of $-F_{12}/F_{11}$ on the scattering angle Θ (= $\pi - \alpha$) for all cloud-particle models used.

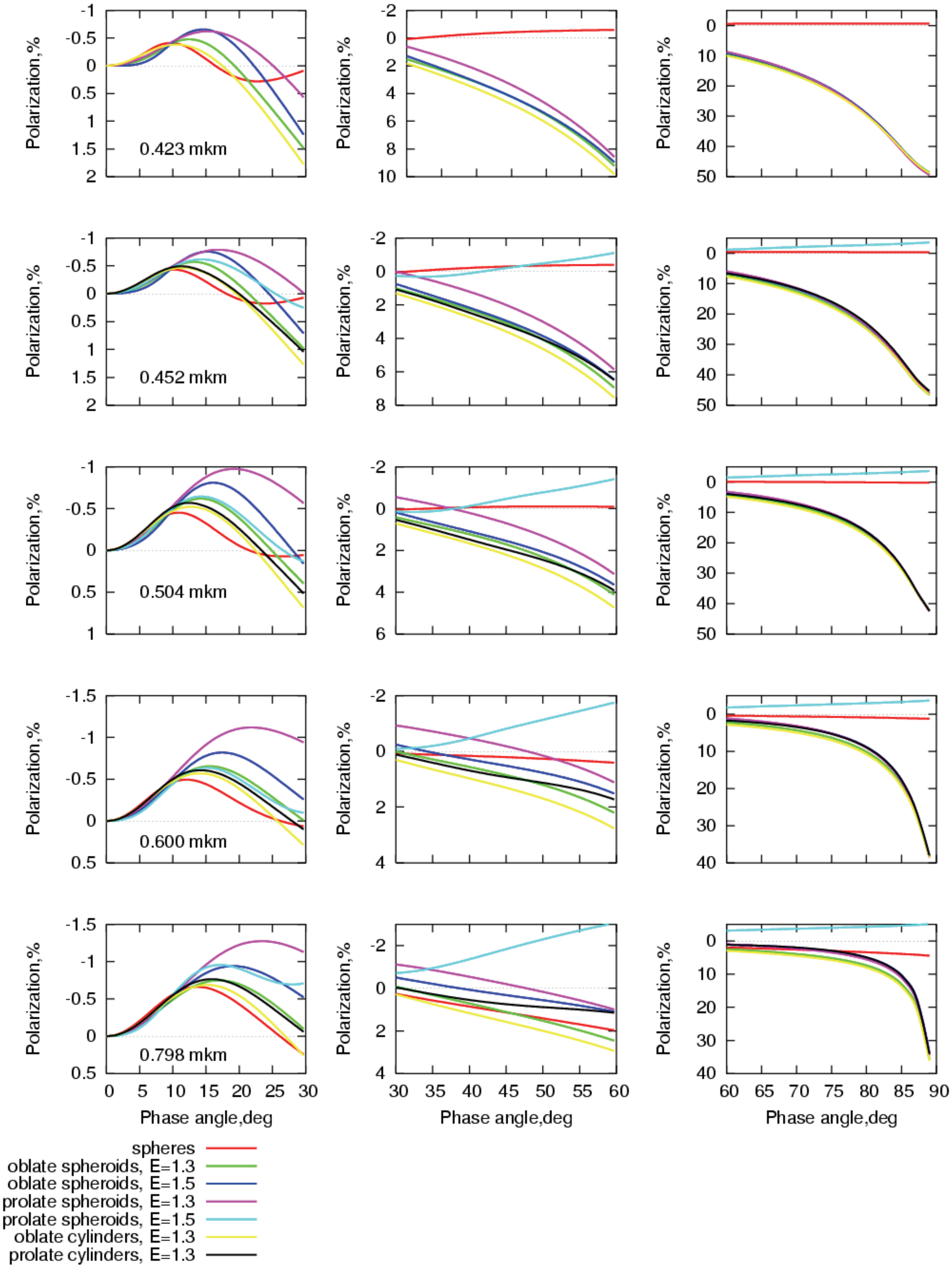

Figure 1. Calculated phase-angle dependence of the polarization at the center of a planetary disk for $0° \le \alpha \le 30°$ (left-hand column), $30° \le \alpha \le 60°$ (middle column), and $60° \le \alpha \le 90°$ (right-hand column).

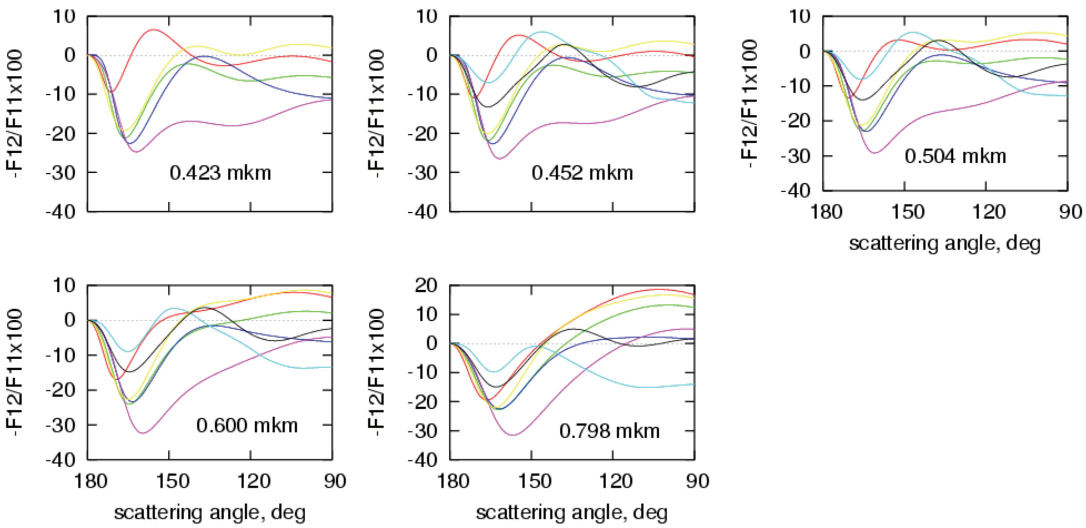

Figure 2. Calculated scattering-angle dependence of the scattering-matrix element ratio $-F_{12} / F_{11}$.

4 Conclusion

Thus, we have demonstrated that phase-angle dependences of the polarization at the center of a planetary disk calculated for various particle cloud models exhibit noticeable differences at larger values of the phase angle. So, we can conclude that the availability of observational data obtained in a wide range of phase angles, e.g., from spacecraft, can provide the necessary constraints on aerosol particle shape and make the problem of the interpretation of polarimetric observations better defined.

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