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Photopolarimetry of planetary atmospheres: what observational data are essential for a unique retrieval of aerosol microphysics?

Janna M. Dlugach[1] and Michael I. Mishchenko[2]★

[1]*Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 27 Zabolotny Street, 03680 Kyiv, Ukraine*

[2]*NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA*

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ABSTRACT

We analyse the results of computations of the intensity and degree of linear polarization of diffusely reflected sunlight for the centre of a planetary disc in the phase-angle range $0^\circ < \alpha < 90^\circ$. The computations are performed using numerically exact *T*-matrix and vector radiative-transfer codes for several alternative models of the Jovian cloud layer derived previously from ground-based spectropolarimetric observations at phase angles $\alpha < 11^\circ$. Our results show that although these models reproduce the existing observational data equally well, they start to show significant polarization differences at phase angles $\alpha \geqslant 12^\circ$. Thus, using Jupiter as a 'proving ground', we conclude that only polarimetric data obtained over a wide range of phase angles (i.e. from spacecraft) may provide definitive constraints on aerosol shape and, as a consequence, ameliorate the ill-posed nature of the inverse remote-sensing problem.

Key words: polarization – scattering – techniques: photometric – techniques: polarimetric – planets and satellites: individual: Jupiter.

1 INTRODUCTION

Polarimetry is one of the most powerful means for the investigation of various astronomical objects in general and planetary atmospheres in particular (Hansen & Travis 1974). Indeed, polarization of the scattered sunlight is extremely sensitive to such properties of aerosols as particle size relative to the wavelength and refractive index, which often makes possible the retrieval of these parameters from polarimetric observations. A classical example of the use of polarimetry in remote sensing is the analysis of ground-based observations of Venus by Hansen & Hovenier (1974). Analogous remote-sensing studies have been carried out for the atmospheres of Jupiter (Morozhenko & Yanovitskii 1973; Mishchenko 1990a) and Saturn (Bugaenko et al. 1975) as well as for dust clouds on Mars during the dust storm of 1971 (Dollfus et al. 1974).

Any retrieval approach used in analyses of polarimetric data requires a model of aerosol particle shape, and in the majority of previous studies the model of spherical particles had been adopted. However, it is generally recognized that ammonia ice crystals may be an important constituent of the Jovian and Saturn's upper atmospheres and are most likely non-spherical (Weidenschilling & Lewis 1973; Slobodkin et al. 1978; Bugaenko & Morozhenko 1981; West, Strobel & Tomasko 1986; Carlson, Lacis & Rossow 1994). The same is true of the ice and dust particles in the Martian atmosphere. It is known (e.g. Mishchenko, Travis & Mackowski 1996; Mishchenko, Travis & Lacis 2002) that in the range of scattering angles Θ greater than 60°, linear polarization is strongly dependent on particle shape (the scattering angle is defined as the angle between the incidence and scattering directions). It should, therefore, be expected that particle non-sphericity can affect in some way the retrieval of aerosol microphysical characteristics such as refractive index and size from remote-sensing data. Hence, an important question is how strong the influence of particle shape on the accuracy of remote-sensing retrievals can be.

In our recent publications (Dlugach & Mishchenko 2004, 2005), we have used Jupiter as a 'proving ground' and have demonstrated that the optical properties of cloud particles (particularly the refractive index) cannot be reliably estimated on the basis of spectropolarimetric measurements performed in a narrow range of phase angles accessible from the Earth. The phase angle α is defined as the angle between the observer and the Sun as viewed from the planet, i.e. $\alpha = 180^\circ - \Theta$. The maximal phase angles accessible from the Earth are $\alpha_{\rm max} \approx 12^\circ$ for Jupiter and $\approx 6^\circ$ for Saturn. Using the results of ground-based spectropolarimetric observations of the centre of the Jovian disc performed by Morozhenko (1976), we have found (Dlugach & Mishchenko 2004, 2005) that an assumption of the shape of cloud particles is essential in estimating their microphysical properties. Specifically, a change in the assumed particle shape can result in significant changes in the retrieved particle refractive index and size as well as atmospheric structure (e.g. the number of atmospheric layers and their characteristics). The main objective of this paper is to clarify what kind of observations can help in the unique determination of particle shape and, as a consequence, yield more accurate retrievals of the microphysical properties of cloud particles.

★E-mail: mmishchenko@giss.nasa.gov

2 ATMOSPHERIC MODELS AND COMPUTATIONAL TECHNIQUES

A detailed analysis of ground-based spectropolarimetric observations of Jupiter based on the model of a homogeneous semi-infinite cloud layer composed of spherical particles was performed by Mishchenko (1990a). Subsequently, the case of non-spherical cloud particles was considered by Dlugach & Mishchenko (2004, 2005). In all three publications, we have used spectropolarimetric data for the centre of the Jovian disc collected by Morozhenko (1976) and spectrophotometric data of Woodman, Cochran & Slavsky (1979). The spectropolarimetric data were obtained at wavelengths $\lambda =$ 0.423, 0.452 0.504, 0.600, 0.798 μm in the phase-angle range $0^\circ < \alpha < 11^\circ$; the absolute error of the measured values of the degree of linear polarization was about 0.1 per cent. The spectrophotometric measurements were performed in the spectral interval 0.3–1.076 μm at a phase angle of 2°, and the relative error was about 10 per cent.

In order to interpret the results of such observations, it is necessary to calculate the components of the specific intensity column vector $\mathbf{I}$ of diffusely reflected radiation. For the centre of a planetary disc, taking into account that the sunlight is unpolarized, the degree of linear polarization is given by $P = -Q/I$. The first two components of the specific intensity column vector, I and Q, are given by (Mishchenko, Travis & Lacis 2006)

$$I(-\mu, \varphi) = \frac{1}{\pi}\mu_0 R_{11}(\mu, \mu_0, \varphi - \varphi_0)F_0, \tag{1}$$

$$Q(-\mu, \varphi) = \frac{1}{\pi}\mu_0 R_{21}(\mu, \mu_0, \varphi - \varphi_0)F_0, \tag{2}$$

where (μ_0, φ_0) and $(-\mu, \varphi)$ specify the directions of light incidence and reflection, respectively, R_{11} and R_{21} are the (1, 1) and (2, 1) elements of the 4×4 Stokes diffuse reflection matrix $\mathbf{R}$, and F_0 is the incident monochromatic energy flux (Hovenier, van der Mee & Domke 2004; Mishchenko et al. 2006). To determine R_{11} and R_{21}, one must first calculate the elements of the single-scattering matrix $\mathbf{F}$ for the particles forming the medium.

In Mishchenko (1990a), the cloud layer of the Jovian atmosphere was assumed to be homogeneous and semi-infinite and to contain gas and homogeneous spherical particles. Particle polydispersity was parameterized in terms of a simple gamma size distribution

$$f(r) = \text{constant} \times r^{(1-3v_{\text{eff}})/v_{\text{eff}}} \exp\left(-\frac{r}{r_{\text{eff}} v_{\text{eff}}}\right), \tag{3}$$

where r is the (surface-equivalent-sphere) radius and r_{eff} and v_{eff} are the effective radius and effective variance of the size distribution, respectively (Hansen & Travis 1974; Mishchenko et al. 2002). The calculation of the elements of the single-scattering matrix $\mathbf{F}$ was performed by using the numerical techniques based on the Lorenz–Mie theory (e.g. de Rooij 1985; Mishchenko et al. 2002). Then, the computation of the elements R_{11} and R_{21} of the diffuse reflection matrix was performed with full account of multiple scattering by means of a numerical solution of the vector form of Ambartsumian's non-linear integral equation as described in de Rooij (1985) and Mishchenko et al. (2006). As a result, a good quantitative 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}, and the effective variance v_{eff} listed in the second row of Table 1 ('A' denotes the case of a one-layer model of the Jovian atmosphere). The corresponding spectral values of the imaginary part of the refractive index m_I were retrieved from the best fit of the computations to the radiance data by Woodman et al. (1979) and are given in the second column of Table 2.

Table 1. Best-fitting microphysical parameter values for various particle and cloud structure models.

Shape	E	m_R	r_{eff}(μm)	v_{eff}	Model
Spheres	1	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

In our subsequent publications (Dlugach & Mishchenko 2004, 2005), we analysed the possible influence of particle shape on the results obtained by Mishchenko (1990a). Two models of the Jovian atmosphere were considered: (A) a homogeneous semi-infinite layer and (B) a two-layer medium with a layer of pure gas of optical thickness τ_g above a semi-infinite homogeneous layer. In both model atmospheres, the semi-infinite homogeneous layer was assumed to consist of non-spherical particles modelled as randomly oriented oblate or prolate spheroids or randomly oriented cylinders with varying aspect ratios E. (The aspect ratio is defined as the ratio of the longest to the shortest axes for spheroids, as the length-to-diameter ratio for prolate cylinders, and as the diameter-to-length ratio for oblate cylinders.) As in Mishchenko (1990a), particle polydispersity was parameterized by the gamma size distribution (3).

Theoretical computations of the elements of the Stokes single-scattering matrix $\mathbf{F}$ for non-spherical particles with sizes comparable to the wavelength are complicated, and by now several numerical techniques have been used for this purpose (e.g. Mishchenko, Hovenier & Travis 2000; Kahnert 2003; Yurkin & Hoekstra 2007). In our studies, we used the FORTRAN *T*-matrix codes developed by Mishchenko & Travis (1998) and ultimately based on the Waterman's *T*-matrix approach (Waterman 1971). Subsequently, the elements R_{11} and R_{21} of the diffuse reflection matrix for model A were computed by means of the numerical solution of Ambartsumian's non-linear integral equation. The overlaying gas layer in model B was incorporated by means of a computational algorithm based on the invariant imbedding technique (Mishchenko 1990b).

The analysis scheme was described in detail by Dlugach & Mishchenko (2004, 2005). An equally good quantitative agreement between the observational data and the model results was found for the atmospheric models and the values of the real part of the refractive index m_R, the effective radius r_{eff}, and the effective variance v_{eff} listed in rows 3–8 of Table 1. Note that for all the versions of model B, the optical thickness of the top gaseous layer τ_g was found to be 0.2 at $\lambda = 0.423$ μm with appropriate values at the other wavelengths consistent with the spectral behaviour of the Rayleigh scattering optical thickness. The corresponding spectral values of the imaginary part of the refractive index m_I retrieved from the spectrophotometric data by Woodman et al. (1979) are given in Table 2. The results listed in Table 1 indicate that even moderate particle asphericity causes significant changes in the retrieved values of the other 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 effective radius can also change by a factor exceeding 2 depending on the assumed particle shape.

Fig. 1 depicts the main results obtained by Mishchenko (1990a) and Dlugach & Mishchenko (2004, 2005). Here, for the wavelength

Table 2. Best-fitting spectral values of the imaginary part of the refractive index m_I.

λ(μm)	Spheres	Oblate spheroids $E = 1.3$	Oblate spheroids $E = 1.5$	Prolate spheroids $E = 1.3$	Prolate spheroids $E = 1.5$	Oblate cylinders $E = 1.3$	Prolate cylinders $E = 1.3$
0.423	0.0012	0.0017	0.0017	0.0020	0.000 65	0.0013	0.0012
0.452	0.0010	0.0013	0.0014	0.0016	0.000 55	0.0010	0.0010
0.504	0.0007	0.0009	0.000 95	0.0011	0.0004	0.0007	0.0007
0.600	0.0006	0.000 75	0.0008	0.0009	0.0004	0.0006	0.0006
0.798	0.0025	0.0032	0.0036	0.0039	0.0022	0.0027	0.0028

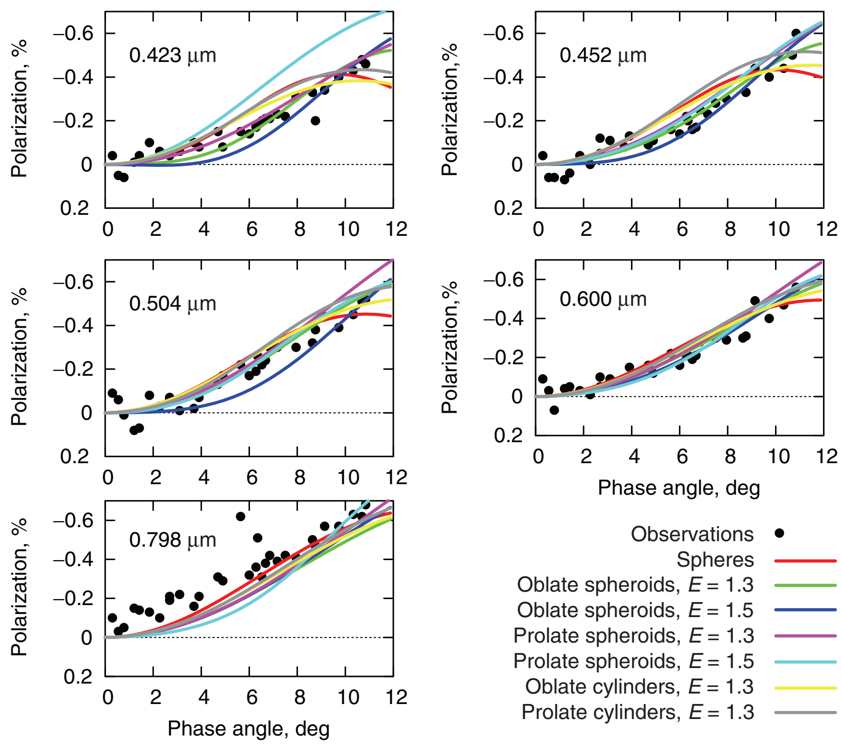

Figure 1. Phase-angle dependence of the degree of linear polarization for the centre of the Jovian disc. The dots show the observational data, the curves depict the results of model computations.

range 0.423–0.798 μm, we visualize the phase-angle dependence of the degree of linear polarization P at the centre of the Jovian disc. The observational data (Morozhenko 1976) are depicted by dots, while the curves show the results of computations for the atmospheric parameters summarized in Tables 1 and 2. One can see indeed that the polarization phase curves computed for the quite different aerosol models agree with the observational data equally well (perhaps with the exception of the case of prolate spheroids with $E = 1.5$ at $\lambda = 0.423$ μm at $\alpha > 6°$). It should be reminded in this regard that the objective of the previous publications was not to determine definitively and unequivocally the actual values of the cloud-particle microphysical parameters, but rather to investigate how strong the dependence of the retrieved values on the assumed particle shape can be. The results obtained allowed us to conclude that the lack of reliable information on the actual particle shape limits one's ability to determine other particle microphysical parameters based on analyses of spectropolarimetric measurements taken within a narrow range of phase angles. It is, thus, important to analyse what kind of observational data can enable the unique determination of the particle microphysical properties.

3 RESULTS OF COMPUTATIONS AND DISCUSSION

To ascertain what kind of spectropolarimetric observational data can facilitate the unique determination of cloud-particle microphysical properties, we analyse how an extension of the phase-angle range can help to determine the particle shape. We have performed calculations of the degree of linear polarization $P(\alpha)$ for the centre of a planetary disc ($\mu_0 = \cos\alpha, \mu = 1$) for the range of phase angles $0° \leqslant \alpha \leqslant 90°$, the spectral interval $\lambda = 0.423$–0.798 μm, and the atmosphere models specified in Tables 1 and 2. The results of these computations are summarized in Fig. 2. For $\alpha > 12°$ and all the wavelengths, one can see significant differences in the behaviour of the polarization curves depending on the adopted cloud-particle model. For instance, in the wavelength range $\lambda = 0.423$–0.504 μm for the case of spheres, the negative polarization has the smallest absolute value (compared to the cases of other particle shapes), and the sign of polarization changes twice (at $\alpha \approx 15°$–$20°$ and 30°). (The reader may recall that the degree of linear polarization P is positive when the plane of polarization is perpendicular to the scattering plane and

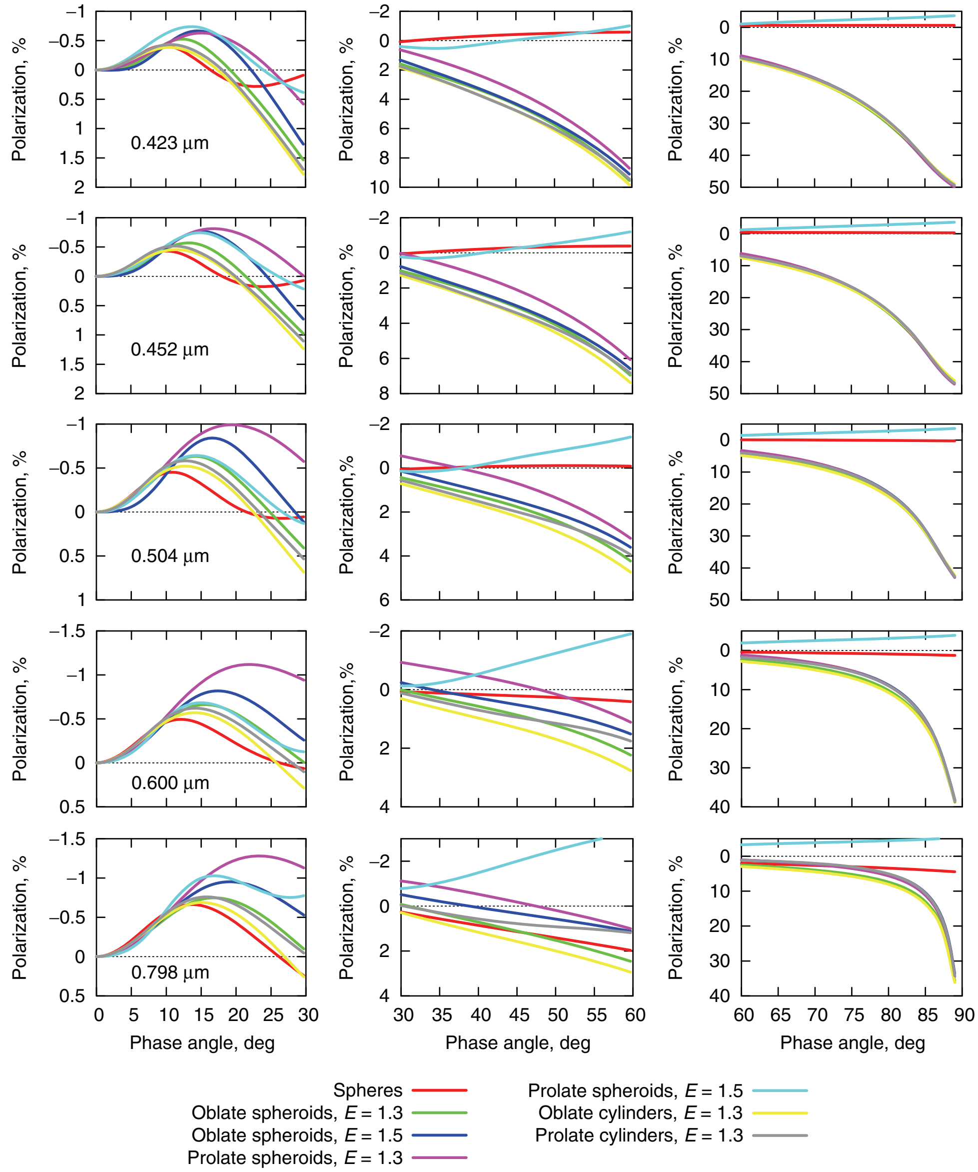

Figure 2. Model phase-angle dependence of the degree of linear polarization for the centre of a planetary disc for $0^\circ < \alpha < 30^\circ$ (left-hand column), $30^\circ < \alpha < 60^\circ$ (middle column) and $60^\circ < \alpha < 90^\circ$ (right-hand column).

negative otherwise.) At longer wavelengths, the sign of polarization changes once at $\alpha \approx 25^\circ$, and then the magnitude of positive polarization increases with increasing phase angle. In the case of prolate spheroids with $E = 1.5$, the behaviour of polarization at $\lambda = 0.452$–0.504 µm is somewhat similar to that in the case of spheres, but at longer wavelengths 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 the phase angle, the polarization becomes positive and increases with increasing phase angle. However, for different particle shapes we see noticeable differences in the position of minimum of negative polarization and of the polarization inversion point, as well as in the values of polarization.

It is well known (see e.g. Hansen 1971; Hovenier et al. 2004; Mishchenko et al. 2006) that a significant contribution to polarization of light diffusely reflected by an optically thick particulate layer comes from the light scattered once. Therefore, it is possible that such varying behaviour of polarization at the centre of a planetary disc is substantially caused by a specific behaviour of the single-scattering matrix element F_{21}. To verify this supposition, we plot in the upper panel of Fig. 3 the calculated phase-angle dependences of $-F_{21}/F_{11}$ for all cloud-particle models used. It is seen indeed that similarly to the case of the phase-angle dependences of diffuse polarization, the values of the ratio $-F_{21}/F_{11}$ agree well with each other for all cloud-particle models concerned if $\alpha < 12^\circ$, but significant differences are observed for larger phase angles. This provides an additional illustration of the strong dependence of F_{12} on the particle microphysical characteristics (shape, refractive index, size, etc.).

However, one can notice a significant difference in the behaviour of P and $-F_{21}/F_{11}$ at larger phase angles which is mainly the consequence of the contribution of the overcloud gas layer to the outgoing radiation for model B. Indeed, it is well known that in the case of

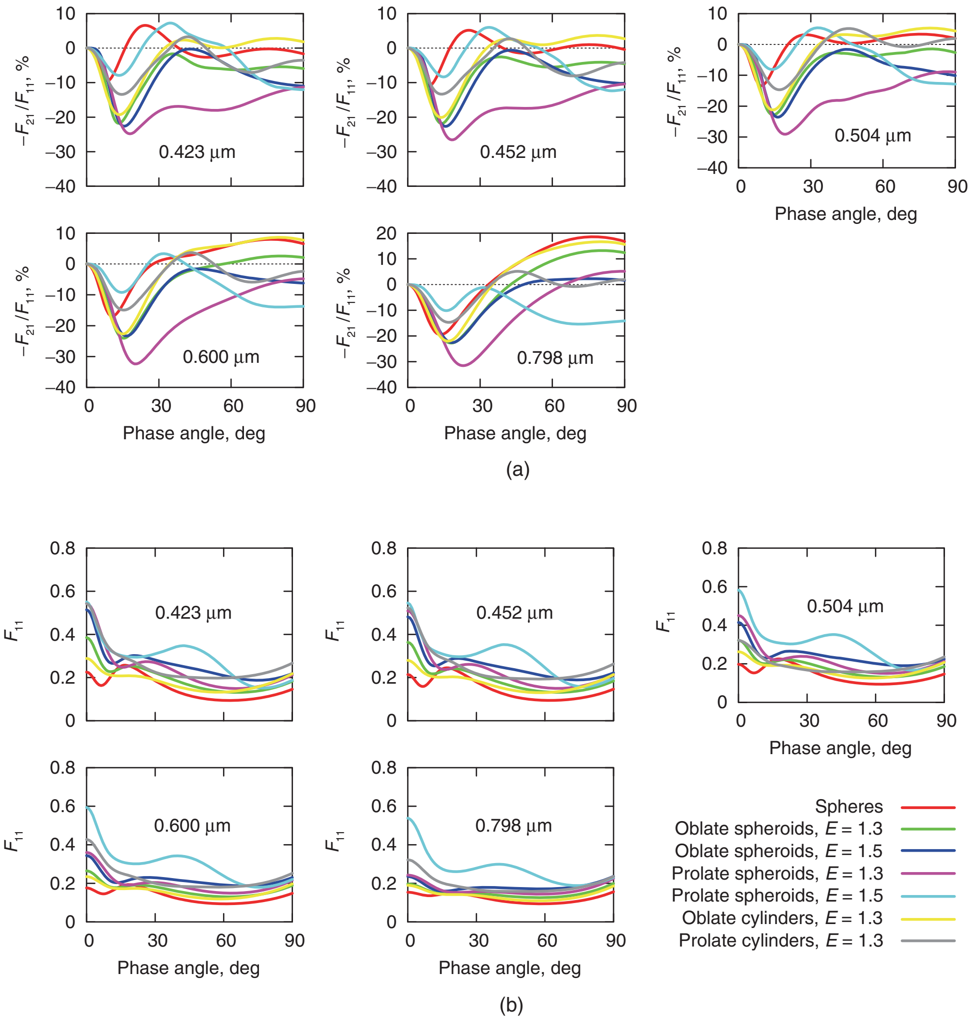

Figure 3. Model phase-angle dependence of the scattering-matrix element ratio $-F_{12}/F_{11}$ (per cent) (a) and the phase function F_{11} (b).

Rayleigh scattering the value of $-F_{21}/F_{11}$ is positive, increases with increasing phase angle, and reaches 100 per cent at $\alpha = 90°$.

Also, it is interesting to analyse the behaviour of the phase-angle dependences of the specific intensity of the diffusely reflected light, *I*. Our previous computations (Dlugach & Mishchenko 2005) performed for various non-spherical particles and surface-equivalent spheres with $m_R = 1.386, r_{\text{eff}} = 0.385$ μm and $v_{\text{eff}} = 0.45$ have shown that in the range of phase angles $0° \leqslant \alpha \leqslant 11°$, the diffuse reflected intensity at the centre of the Jovian disc depends weakly on particle shape. In the bottom panel of Fig. 3, we demonstrate the theoretical phase-angle dependence of the scattering matrix element F_{11}, i.e. the phase function, over a wider range of phase angles, $0° \leqslant \alpha \leqslant 90°$. Note that the phase function is normalized according to

$$\frac{1}{2}\int_0^\pi \mathrm{d}\alpha \sin\alpha F_{11}(\alpha) = 1. \tag{4}$$

A quite pronounced dependence on particle model is seen, especially for $\alpha < 60°$. Fig. 4 illustrates the phase-angle dependences of the diffuse reflected intensity $I(\alpha)\,(\mu_0 = \cos\alpha, \mu = 1, 0° \leqslant \alpha \leqslant 90°)$ calculated for all the cloud models listed in Tables 1 and 2 assuming, for simplicity, that $F = \pi$. One can see that in spite of the varying behaviour of F_{11}, the values of $I(\alpha)$ differ from each other by no more that about 10 per cent (with the exception of the range of $\alpha >$ 70°, where the specific intensity is very small). This result illustrates once again the predominant contribution of multiple scattering to the diffuse reflected intensity at the centre of a planetary disc. Because the absolute accuracy of radiometric measurements is typically of order of 5 per cent and can be significantly worse for weak signals, we can conclude that measurements of the phase-angle dependence of the reflected intensity do not provide useful information on the cloud-particle shape.

4 CONCLUSIONS

On the basis of accurate single- and multiple-scattering computations with full account of polarization, we have demonstrated that although polarization phase curves for various cloud-particle models can be very close to each other in the phase-angle range $0° < \alpha < 11°$, they exhibit significant differences at larger phase angles. Our results indicate unequivocally that the availability of observational data obtained in a wide range of phase angles, i.e. from spacecraft, is critical because it may provide the necessary constraints on aerosol particle shape and thereby make the problem of the interpretation of spectropolarimetric observations sufficiently well posed.

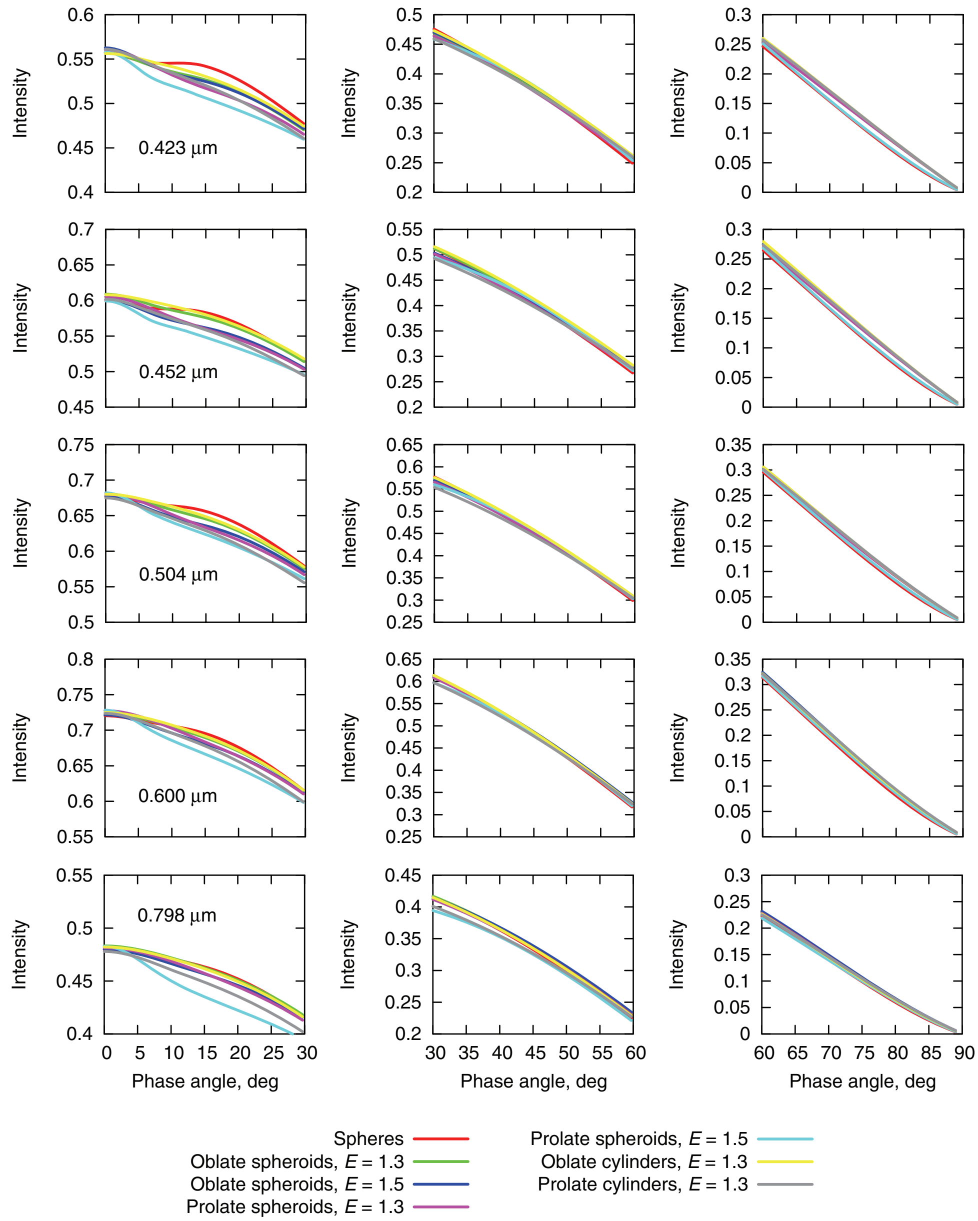

Figure 4. Model phase-angle dependence of the intensity of the diffusely reflected radiation at the centre of a planetary disc for $0^\circ < \alpha < 30^\circ$ (left-hand column), $30^\circ < \alpha < 60^\circ$ (middle column) and $60^\circ < \alpha < 90^\circ$ (right-hand column).

The problem of remote-sensing retrievals of microphysical properties of morphologically complex cloud particles in the Jovian atmosphere remains very difficult (e.g. West et al. 1986). Previous analyses of photopolarimetric data obtained from Pioneers 10 and 11 (Smith & Tomasko 1984; Smith 1986) as well as from the Galileo Orbiter (Braak et al. 2002) have been based on synthetic scattering matrices not related directly to aerosol microphysical properties. In contrast, the *T*-matrix method employed in this study has a wide range of applicability and can be used to model the scattering matrices of realistic particles such as irregular mineral grains and random fractal aggregates (e.g. Mishchenko et al. 2004; Dubovik et al. 2006; Liu & Mishchenko 2007; Mishchenko et al. 2007; Wriedt 2007; Yang et al. 2007). Other modern theoretical techniques can also be used to simulate scattering matrices of particles with more complex morphologies (e.g. Mishchenko et al. 2000; Kahnert 2003; Yurkin & Hoekstra 2007) should data analysis necessitate that. Important constraints on theoretical single-scattering models can be provided by advanced laboratory measurements for well-characterized particle samples (e.g. Hovenier et al. 2003; Hadamcik et al. 2007). We hope, therefore, that our paper will help to formulate the framework for improved microphysical retrieval of aerosol and cloud particles in the Jovian atmosphere as well as in other planetary atmospheres.

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