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Physical Properties of the Upper Tropospheric Aerosols in the Equatorial Region of Jupiter

M. I. MISHCHENKO

Laboratory for Radiative Transfer Theory, The Main Astronomical Observatory of the Ukrainian Academy of Sciences, 252127 Kiev-127, Goloseevo, USSR

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Physical properties of the upper tropospheric aerosols in the Equatorial Region of Jupiter are estimated by means of interpretation of ground-based spectropolarimetric and spectrophotometric observations of the center of the Jovian disk. It was assumed that the upper cloud layer of the Jovian atmosphere is homogeneous and optically thick (semi-infinite), and contains gas and homogeneous spherical particles. Two different particle size distributions were used, namely a gamma distribution and modified gamma distribution. The best agreement between the observational data and computations for both size distributions was found for an effective radius of aerosols $r_{\mathrm{eff}} = 0.39 \pm 0.08\ \mu\mathrm{m}$ and a real part of the refractive index $n_r = 1.39 \pm 0.01$. The results were obtained by means of multiple scattering calculations with full account of polarization. © 1990 Academic Press, Inc.

I. INTRODUCTION

Within the past decade there has been a great deal of activity in the investigation of the aerosol component of the Jovian atmosphere. We do not aim here to discuss corresponding publications in detail and only note papers of Bézard *et al.* (1983), Griffin *et al.* (1986), Marten *et al.* (1981), Orton *et al.* (1982), Sato and Hansen (1979), Smith (1986), Smith and Tomasko (1984), Stoker and Hord (1985), Tomasko *et al.* (1978), Tomasko *et al.* (1986), West (1979), West (1988), and West *et al.* (1985), referring the reader to the excellent review of West *et al.* (1986). Analysis of the mentioned papers shows that primarily spectrophotometric observational data in visible, infrared, submillimeter, and millimeter spectral regions were used to estimate the mean radius of the Jovian tropospheric aerosols. The results of different authors are highly ambiguous and significantly influenced by the amount and accuracy of available observational and laboratory data, as well as by incompleteness of theoretical results for nonspherical scattering particles. The refractive index of aerosols was not estimated. Usually it was a priori assumed that the tropospheric aerosols mainly consist of ammonia.

It is well known that the best way to determine physical properties of cloud particles is to interpret results of polarimetric measurements of reflected sunlight (see e.g., Coffeen and Hansen 1974). Nevertheless, in the papers of Smith (1986) and Smith and Tomasko (1984), dealing with the interpretation of the polarimetric data from the Pioneer 10 and 11 spacecraft, the determination of physical properties of aerosols was not considered, because it was assumed that aerosols in the upper Jovian atmosphere are most likely nonspherical. Instead of this, some formal quantities specifying the scattering medium were determined, first of all the single scattering albedo and parameters of a model scatter-

ing matrix, chosen irrespective of shape, size, and refractive index of cloud particles (some reasons for such choice are given by Smith and Tomasko 1984, and Tomasko and Smith 1982).

Summarizing the results of previous investigations West *et al.* (1986) propose that available thermal and photometry/polarimetry observational data may be reconciled, if in zones large particles ($r \sim 3$–50 μm) are located near the base of the NH_3 cloud, whereas small particles ($r \sim 1$ μm) are concentrated near its top and have an optical depth of $\sim$1–5 in visible light; in belts only small particles are likely to be present. West *et al.* (1986) also note that while the proposed particle distribution seems to be able to fit a variety of data and is consistent with cloud microphysical predictions of Rossow (1978), quantitative models are needed.

In the present paper we have tried to estimate physical parameters of the upper tropospheric aerosols in the Equatorial Region of Jupiter by means of interpretation of the ground-based spectropolarimetric observations of Morozhenko (1976) and spectrophotometric observations of Woodman *et al.* (1979). Only the measurements related to the center of the Jovian disk were taken into account. We have used the simplest optical model to describe the upper Jovian atmosphere—semi-infinite homogeneous layer consisting of gas and spherical aerosols. This choice of observational data and atmospheric model was motivated by the following reasons.

(i) Unlike the polarimetry from Pioneers 10 and 11, the ground-based observations of Jupiter pertain to small phase angles: $\alpha \lesssim 12°$. According to De Rooij (1985), the linear polarization of reflected sunlight at small phase angles is especially sensitive to aerosol parameters.

(ii) Polarization of reflected sunlight is not affected by aerosols concentrated at optical depths larger than several units (see e.g., De Rooij 1985). Because, according to Sato and Hansen (1979), Smith (1986), and West *et al.* (1985), the upper tropospheric cloud is optically thick, one can consider the cloud to be semi-infinite.

(iii) The haze and clear gas layers, located above the upper tropospheric cloud in the Equatorial Region of Jupiter, are optically thin (Gehrels *et al.* 1969, West 1988). When angles of incidence and reflection of sunlight are close to zero (the situation pertinent to ground-based observations of the center of the Jovian disk) the sunlight penetrates these layers mostly undisturbed; thus, we have assumed that in the first approximation the effect of these layers on the Stokes parameters of the reflected sunlight can be neglected.

(iv) Linear polarization of reflected sunlight in the center of the Jovian disk is close to zero (Morozhenko and Yanovitskij 1973, Morozhenko 1976). Therefore, one can assume the scattering medium to be isotropic and nonspherical (generally speaking) aerosols to be randomly oriented. Unfortunately, computational techniques for nonspherical scattering particles are still too time-consuming (see e.g., De Haan 1987, Wiscombe and Mugnai 1986), and usually it is difficult to use them in extensive computations. There are two ways to overcome the difficulty. The first one is to use some parametrization of the scattering matrix (e.g., Smith 1986, Smith and Tomasko 1984, White 1979) and to leave open the question of the physical parameters of aerosols. The second way is to replace randomly oriented nonspherical aerosols by equivalent (e.g., equal-volume) spheres and to consider determined values of aerosol parameters as a first approximation to real ones. Because our goal was to estimate the size and refractive index of the Jovian tropospheric aerosols, we have used the second approach.

(v) Only the central point of the Jovian disk was considered, and only the measurements pertaining to this point were used in our analysis. Therefore, all questions of the latitudinal and longitudinal inhomogeneity (see e.g., Gehrels *et al.* 1969, Teifel

1985, West 1988, West *et al.* 1986) of the Jovian atmosphere were removed as well as questions regarding the correctness of the utilization of a single atmospheric model to interpret observations of different points on the disk, or of the whole disk.

(vi) The atmospheric model chosen is specified by a minimum number of free parameters, and we expected that all of these parameters could be uniquely determined from the available observational data.

II. MODEL CALCULATIONS AND DISCUSSION

Spectropolarimetric data of Morozhenko (1976) were obtained during June/October, 1973 with the 0.7-m reflector of the Main Astronomical Observatory of the Ukrainian Academy of Sciences. Interference filters were used centered at $\lambda = 4230, 4520, 5040, 6000, 7270$, and 7980 Å. The bandwidths of the filters were $\Delta\lambda = 0.02\ \lambda$. The absolute error of the measured values of the degree of linear polarization was about 0.1%. The range of phase angles 0° to 11° was scanned.

Spectrophotometric data of Woodman *et al.* (1979) were obtained with the 2.7-m telescope of the McDonald Observatory during the night of November 9, 1976. The spectra in the wavelength region 3000 to 10760 Å were obtained at a phase angle of 2°. The spectral resolution was 8 Å for the "blue" region 3000 to 6600 Å, and 16 Å for the "red" region 6600 to 10760 Å. The overall uncertainty in the reflectivity values was about 8 to 10%.

Despite the 3-year interval between the polarimetric and photometric observations we have assumed that the Jovian atmosphere was sufficiently stable during this period, and the results of our analysis were not significantly influenced by possible time variations.

As pointed out, we have assumed the upper cloud layer to be homogeneous, semi-infinite and composed of gas and spherical aerosols. For the sake of simplicity, it was assumed that the real part of the aerosol reflective index is constant in the wavelength region 4230 to 7980 Å, and that aerosols are the major absorbers in the gas–aerosol mixture at 4230, 4520, 5040, 6000, and 7980 Å. The data at 7270 Å were not used in our analysis, because they pertain to the center of a strong methane absorption band. In such a case the polarization of reflected light is significantly influenced by the upper haze and the gas layers, which are not described by our model.

In our analysis we have used Deirmendjian's particle size distribution

$$n(r) = Cr^a \exp[-a(r/r_c)^\gamma/\gamma], \quad 0 \le r < \infty,$$

with

$$C = \gamma(a/\gamma)^{(a+1)/\gamma}\{r_c^{a+1}\Gamma[(a+1)/\gamma]\}^{-1}, \quad (1)$$

where r is particle radius, Γ is the gamma-function, a, γ, and r_c are parameters. The constant C is chosen such that

$$\int_0^\infty n(r)\, dr = 1.$$

The effective radius, r_{eff}, and the effective variance, v_{eff}, corresponding to the distribution (1), are

$$r_{\text{eff}} = (1/G)\int_0^\infty n(r)\pi r^3\, dr = (a/\gamma)^{-1/\gamma} r_c \Gamma[(a+4)/\gamma]/\Gamma[(a+3)/\gamma], \quad (2)$$

$$v_{\text{eff}} = (Gr_{\text{eff}}^2)^{-1}\int_0^\infty n(r)\pi r^2 (r - r_{\text{eff}})^2\, dr = \Gamma[(a+3)/\gamma]\Gamma[(a+5)/\gamma]/\Gamma^2[(a+4)/\gamma] - 1, \quad (3)$$

where

$$G = \int_0^\infty n(r)\pi r^2\, dr.$$

Two values of the parameter γ were used in our computations. First, we have used the value $\gamma = 1$. This value corresponds to standard gamma distribution (e.g., Hansen 1971b)

$$n(r) = C_1 r^{(1-3v_{\text{eff}})/v_{\text{eff}}} \exp[-r/(v_{\text{eff}} r_{\text{eff}})], \quad (4)$$

where

$$C_1 = \{r_{\text{eff}} v_{\text{eff}} \Gamma [(1 - 2v_{\text{eff}})/v_{\text{eff}}]\}^{-1} (r_{\text{eff}} v_{\text{eff}})^{(3v_{\text{eff}}-1)/v_{\text{eff}}},$$

$$r_{\text{eff}} = r_c(a + 3)/a,$$

$$v_{\text{eff}} = 1/(a + 3) < 0.5.$$

For calculating the reflectivity, R, and the degree of linear polarization of reflected sunlight, P, for the center of the Jovian disk we have used the formulas

$$R(\alpha) = R^0_{11}(1, \mu_0), \quad (5)$$

$$P(\alpha) = -2\,[R^2_{21}(1, \mu_0)/R(\alpha)] \cdot 100\%, \quad (6)$$

where $\mathbf{R}^s(\mu, \mu_0)$ are azimuthal components of the reflection matrix in the (I, Q, U, V)-representation of the Stokes vector, $\mu_0 = \cos\theta_0$, $\mu = \cos\theta$, θ_0 and θ are polar angles of incidence and reflection of sunlight, α is phase angle. For the center of a planetary disk $\mu_0 = \cos\alpha$, $\mu = 1$, and only zero and second azimuthal components of the reflection matrix contribute to the Stokes vector of reflected light (Hovenier and De Haan 1985).

Azimuthal components of the reflection matrix for the semi-infinite homogeneous atmosphere were computed by means of numerical solution of Ambartsumian's nonlinear integral equation (see e.g., Domke 1975b)

$$\begin{aligned}(\mu + \mu_0)\mathbf{R}^s(\mu, \mu_0) &= w\mathbf{Z}^s(-\mu, \mu_0)/4 \\ &+ (w\mu/2)\int_0^1 \mathbf{R}^s(\mu, \mu')\,\mathbf{Z}^s(\mu', \mu_0)\,d\mu' \\ &+ (w\mu_0/2)\int_0^1 \mathbf{Z}^s(-\mu, -\mu')\,\mathbf{R}^s(\mu', \mu_0)\,d\mu' \\ &+ w\mu\mu_0 \int_0^1\int_0^1 \mathbf{R}^s(\mu, \mu') \\ &\quad \mathbf{Z}^s(\mu', -\mu'')\,\mathbf{R}^s(\mu'', \mu_0)\,d\mu'\,d\mu'', \quad (7)\end{aligned}$$

where w is the single scattering albedo and $\mathbf{Z}^s$ are azimuthal components of the phase matrix. We have used the computational procedure proposed by Dlugach and Yanovitskij (1974) for the scalar case, and extend by De Rooij (1985) to the vector case. It was shown by De Rooij (1985) that for optically thick atmospheres the procedure is a good alternative for the doubling method (Van de Hulst 1980, Hansen 1971a, Hovenier 1971, De Haan *et al.* 1987) and for the order of scattering method (Uesugi and Irvine 1970, Van de Hulst 1980, Mukai and Mukai 1979). The second azimuthal component of the reflection matrix was calculated using the three-by-three approximation (Hansen 1971b). For computing azimuthal components of the phase matrix for spherical polydispersions we have used the approach proposed by Domke (1975a) and reconsidered by De Rooij and Van der Stap (1984). Mie coefficients, a_n and b_n, were computed by means of the numerical procedure described by Wiscombe (1980). The number of quadrature division points in the numerical evaluation of the integrals in Eq. (7) was chosen such that the accuracy of the computed values of the degree of linear polarization was better than 0.01%.

Spectropolarimetric data for the center of the Jovian disk (Morozhenko 1976) are given in Figs. 1 and 2 (dots). The data show that theoretical polarization phase curves must be practically independent of wavelength in the wavelength region 4230 to 7980 Å. This requirement is very important and imposes strong limitations on the value of the effective variance, v_{eff}. Extensive computations have shown that the requirement can not be satisfied if $v_{\text{eff}} < 0.4$. On the other hand, values $0.4 < v_{\text{eff}} < 0.5$ give nearly equal values of the reflectivity and polarization. Therefore, in all our further computations we have used the value $v_{\text{eff}} = 0.45$. Apparently it is impossible to determine the parameter v_{eff} more accurately than to indicate the interval (0.4; 0.5) of its possible values.

Further analysis of the observational data was made as follows. First, values of the real part of the refractive index of aerosols, n_r, from the interval (1.1; 2.2) were set in consecutive order. Then parameters n_i (imaginary part of the refractive index) and r_{eff} were varied in order to achieve satisfactory agreement between computations and

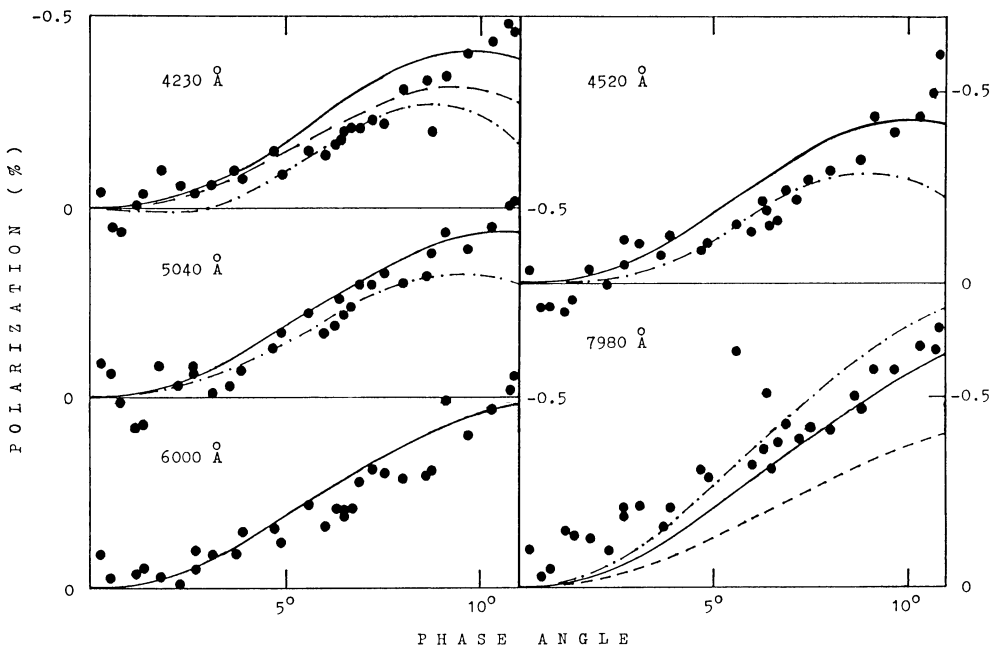

FIG. 1. Phase angle dependence of the degree of linear polarization for the center of the Jovian disk. Dots are the results of observations (Morozhenko 1976). Curves are the results of model computations for a gamma particle size distribution with $v_{\rm eff} = 0.45$, and for the values of $n_{\rm i}$ from Table I. Solid curves are computed for $r_{\rm eff} = 0.385$ μm, $n_{\rm r} = 1.386$, $f_{\rm R} = 0$. The short-dash curve is computed for $r_{\rm eff} = 0.31$ μm, $n_{\rm r} = 1.386$, $f_{\rm R} = 0$. Dot-dash curves are computed for $r_{\rm eff} = 0.47$ μm, $n_{\rm r} = 1.386$, $f_{\rm R} = 0$. The long-dash curve is computed for $r_{\rm eff} = 0.385$ μm, $n_{\rm r} = 1.386$, $n_{\rm i} = 0.0011$, $f_{\rm R} = 0.04$ (the parameter $n_{\rm i}$ was slightly changed to obtain the same reflectivity as for $n_{\rm i} = 0.0012$ and $f_{\rm R} = 0$).

the observational data at 7980 Å, where the influence of gas scattering can be neglected. Thus, it was possible to determine the parameters $n_{\rm i}$ and $r_{\rm eff}$ using the measured values of the reflectivity and the phase dependence of the degree of linear polarization. Then computations were made at 6000 Å. If it was necessary, Rayleigh scattering was taken into account; i.e., a nonzero value of the parameter $f_{\rm R} = k_{\rm sca,R}/k_{\rm sca,a}$ was introduced, where $k_{\rm sca,R}$ and $k_{\rm sca,a}$ are the gas and aerosol scattering coefficients, respectively. Then computations were made at 5040 Å, and so on.

The procedure described above was continued until sufficiently good agreement was achieved between the observational data and computations at 4230, 4520, 5040, 6000, and 7980 Å for some values of the parameters $n_{\rm r}$, $n_{\rm i}$, and $r_{\rm eff}$. It was found that the values $r_{\rm eff} = 0.385$ μm and $n_{\rm r} = 1.386$ provide the best agreement (see Fig. 1). The corresponding spectral values of the parameter $n_{\rm i}$ are listed in Table I. Computations have shown that the reflectivity, R, is

TABLE I

SPECTRAL VALUES OF THE IMAGINARY PART OF THE REFRACTIVE INDEX, $n_{\rm i}$, ALBEDO FOR SINGLE SCATTERING, w, AND ASYMMETRY PARAMETER OF THE PHASE FUNCTION, g

	$n_{\rm i}$	w	g
4230 Å	0.0012	0.987	0.764
4520 Å	0.0010	0.990	0.764
5040 Å	0.0007	0.994	0.765
6000 Å	0.0006	0.995	0.765
7980 Å	0.0025	0.983	0.761

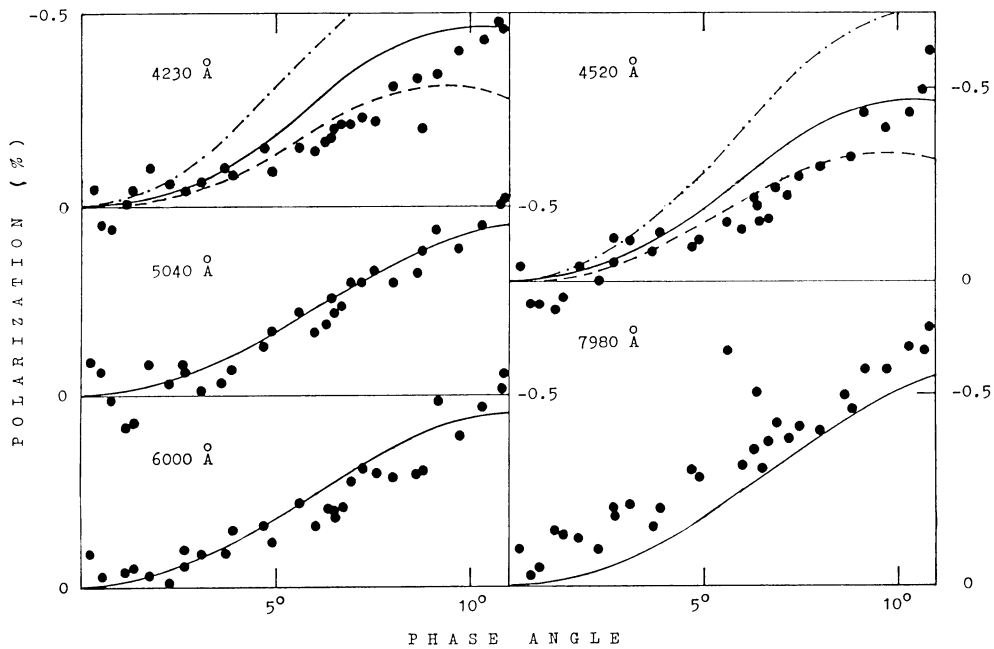

FIG. 2. Same as Fig. 1. Dash curves are computed for $r_{\mathrm{eff}} = 0.385\ \mu\mathrm{m}$, $n_r = 1.38$, $f_R = 0$. Dot-dash curves are computed for $r_{\mathrm{eff}} = 0.385\ \mu\mathrm{m}$, $n_r = 1.40$, $f_R = 0$. Solid curves are computed for $n_r = 1.386$, $f_R = 0$, and Deirmendjian's particle size distribution with parameters $a = 1.66$, $\gamma = \frac{1}{2}$, $r_c = 0.0447\ \mu\mathrm{m}$.

practically independent of r_{eff} in the interval (0.31; 0.47) μm and of n_r in the interval (1.38; 1.40). The corresponding computed polarization phase curves are given in Figs. 1 and 2. Using these numerical results we can estimate inaccuracies of the determined values of the model parameters to be: $r_{\mathrm{eff}} = 0.39 \pm 0.08\,\mu\mathrm{m}$, $n_r = 1.39 \pm 0.01$. Unfortunately, the contribution of Rayleigh scattering cannot be determined confidently, because introducing even the small nonzero value of the parameter f_R only worsens the fit of the theoretical polarization phase curves to the observational data. The most that can be said is that f_R is very small (see Fig. 1 where as an example the long-dash curve at 4230 Å is computed for $f_R = 0.04$).

Computed spectral values of the single-scattering albedo, w, and the asymmetry parameter of the phase function, g, are listed in Table I for the best-fitting aerosol parameters. Spectral values of the element $F_{11}(\theta)$ (phase function) and of the ratio $p(\theta) = -F_{21}(\theta)/F_{11}(\theta)$ of the elements of the Mie scattering matrix are given in Table II, θ being the scattering angle, and the ratio $p(\theta)$ being the degree of linear polarization for single scattering of unpolarized incident light. It should be noted that our values of the asymmetry parameter of the phase function, g, and their very slight dependence on wavelength are in good agreement with the results of Tomasko *et al.* (1978).

We have also studied how the results of our analysis are influenced by the particular choice of the particle size distribution function. For this purpose we have used the distribution (1) with the parameter $\gamma = \frac{1}{2}$. Such a distribution is characterized by a longer "tail" and, contrary to the distribution (4) with $v_{\mathrm{eff}} = 0.45$, by the value $n(0) = 0$. Polarization phase curves computed for the values $n_r = 1.386$, $a = 1.66$, $r_c = 0.0447\ \mu\mathrm{m}$, and for the values of the parameter n_i from Table I are shown in Fig. 2 (solid lines). Corresponding values of the effective ra-

TABLE II

PHASE FUNCTION, F_{11}, AND POLARIZATION FOR SINGLE SCATTERING OF UNPOLARIZED INCIDENT LIGHT, $p = -F_{21}/F_{11}$, FOR THE BEST-FITTING AEROSOL PARAMETERS

θ	7980 Å		6000 Å		5040 Å		4520 Å		4230 Å	
	F_{11}	p	F_{11}	p	F_{11}	p	F_{11}	p	F_{11}	p
0°	20.39	0.0	26.00	0.0	30.83	0.0	34.81	0.0	37.71	0.0
5°	18.87	−0.0006	23.07	−0.0013	26.21	−0.0017	28.52	−0.0019	30.08	−0.0020
10°	15.30	−0.0022	17.10	−0.0047	17.95	−0.0058	18.39	−0.0063	18.61	−0.0065
20°	8.062	−0.0049	7.865	−0.0128	7.586	−0.0158	7.369	−0.0169	7.225	−0.0173
40°	1.932	0.0089	1.777	−0.0197	1.709	−0.0322	1.672	−0.0381	1.651	−0.0412
60°	0.567	0.0602	0.525	−0.0004	0.513	−0.0289	0.508	−0.0435	0.505	−0.0515
80°	0.222	0.1354	0.209	0.0431	0.206	0.0003	0.205	−0.0220	0.204	−0.0343
100°	0.120	0.1848	0.115	0.0787	0.114	0.0320	0.114	0.0086	0.114	−0.0038
120°	0.094	0.1530	0.094	0.0614	0.094	0.0179	0.094	−0.0049	0.094	−0.0174
140°	0.110	0.0483	0.121	0.0250	0.128	0.0090	0.131	−0.0014	0.133	−0.0075
150°	0.132	−0.0307	0.156	0.0093	0.172	0.0303	0.180	0.0407	0.185	0.0466
160°	0.149	−0.1450	0.193	−0.0634	0.222	−0.0051	0.239	0.0286	0.249	0.0482
170°	0.136	−0.1663	0.154	−0.1685	0.172	−0.1332	0.186	−0.1055	0.196	−0.0885
175°	0.144	−0.0575	0.152	−0.0696	0.160	−0.0624	0.165	−0.0525	0.170	−0.0450
180°	0.154	0.0	0.176	0.0	0.198	0.0	0.214	0.	0.226	0.0

dius and the effective variance are $r_{\text{eff}} = 0.39\ \mu\text{m}$, $v_{\text{eff}} = 0.45$. One can see that two different particle size distributions, characterized by the same values of the parameters r_{eff} and v_{eff}, give essentially coincident polarization phase curves. As for the reflectivity, the maximum absolute difference between computed values of R for these two size distributions is less than 0.003. Thus, for multiple-scattering processes the parameters r_{eff} and v_{eff} are more important than the formal parameters describing the shape of a distribution. The same conclusion for the case of single scattering was made previously by Hansen and Travis (1974).

In the above analysis we have assigned all of the absorption in the gas/aerosol mixture to aerosols by introducing a nonzero imaginary part of the aerosols refractive index. To study how such assignment can influence our results, we have also considered the case of nonabsorbing aerosols and absorbing gas. For this purpose computations have been made for the parameters $r_{\text{eff}} = 0.385\ \mu\text{m}$, $n_r = 1.386$, $n_i = 0$, and for the values of the single-scattering albedo from Table I. We have found that nonabsorbing aerosols and absorbing gas produce practically the same reflectivity and degree of linear polarization, as absorbing aerosols and nonabsorbing gas do, the maximum absolute difference being less than 0.004 for the reflectivity, and less than 0.04% for the degree of linear polarization. This result can be explained by the fact that the phase function, $F_{11}(\theta)$, and the degree of linear polarization for single scattering of unpolarized incident light, $p(\theta)$, are practically independent of n_i if $n_i \lesssim 0.003$ (see e.g., De Rooij 1985). Thus, although we are unable to answer the question of how gas and aerosols contribute to the absorption at 4230, 4520, 5040, 6000, and 7980 Å, the answer is not important if only the parameters r_{eff}, v_{eff}, and n_r are to be determined.

Finally, it should be noted that similar ground-based polarimetric data were interpreted earlier by Morozhenko and Yanovitskij (1973). These authors used the same atmospheric model (semi-infinite homogeneous layer composed of gas and spherical aerosols), but, contrary to our work, they used an approximate formula to

calculate polarization phase curves for the center of the Jovian disk. Although the range of validity of this formula and its accuracy are unknown a priori, Morozhenko and Yanovitskij have obtained results which are surprisingly good agreement with ours. From their analysis they have derived the values $n_r \simeq 1.36$, $r_0 \simeq 0.2$ μm, and $\sigma^2 \simeq 0.30$, where r_0 and σ are the parameters of the log-normal particle size distribution,

$$n(r) = \exp[-\ln^2(r/r_0)/(2\sigma^2)]/[(2\pi)^{1/2}\sigma r].$$

One can easily show that for this distribution

$$r_{\text{eff}} = r_0 \exp(5\sigma^2/2) \simeq 0.4\ \mu\text{m},$$

$$v_{\text{eff}} = \exp(\sigma^2) - 1 \simeq 0.35.$$

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