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ОПТИКА КЛАСТЕРОВ, АЭРОЗОЛЕЙ И ГИДРОЗОЛЕЙ

Looking for a glory in *A*-water clouds

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In this paper we discuss a hypothesis proposed by Anatoly N. Nevzorov that considerable amount of water in cold clouds can exist in a specific phase state with the refractive index ≈ 1.8 and density higher than 2 g/cm^3 (so called *A*-water). One of the arguments mentioned in favor of this hypothesis is that the glory phenomenon can be better explained by existence of *A*-water. In our paper we consider this argument in detail studying the phase functions of A-water clouds for different distributions of droplet size.

Keywords: clouds, *A*-water, glory, rainbow, halo, phase function, polarization.

Introduction

In addition to ordinary natural water with density 1 g/cm^3 and refractive index 1.33, there are known several metastable states with different internal structure and macrophysical properties (see, for example, [1]). According to [2], A.N. Nevzorov detected stable existence of liquid-droplet amorphous water (*A*-water) in atmospheric clouds and measured some of its properties [3–9]. A-water is claimed to be one of metastable states with density ≈ 2.1g/cm^3 and refractive index ≈ 1.82. More over, A.N. Nevzorov insists that the glory phenomenon can be described properly only by existence of *A*-water in clouds [9]. The last statement was earlier refuted in [10], were the authors asserted that glory can appear in ordinary water-drop clouds, and there is no need to introduce *A*-water (see, in addition, [11–13]).

It was mentioned in [14] that for monodisperse media computation results, presented in [8], are in contradiction to the Mie theory. Unfortunately, no detailed information can be found in papers of A.N. Nevzorov about distributions of droplet size that he used to compute phase functions of clouds with *A*-water. It complicates evaluation of his hypothesis because distribution of droplet size highly affects the phase function and formation of glory. In our paper we want to fill up the gap by studying phase functions of clouds with different size distributions for *A*-water droplets. First, we consider distributions, which are used for conventional cloud models. Then we consider the case of "narrow" distributions, which is more interesting for studying glory phenomenon. To compute phase functions we used program POLYMIE, which is freely available on Internet. This program was originally developed in Ludwig-Maximilian University of Munich on the basis of Mie code by W. Wiscomb [15]. Additional modifications, introduced later in the program, enable one to perform computations with high accuracy for an arbitrary droplet size distribution.

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1. Phase functions of *A*-water clouds with conventional droplet size distributions

Modified Gamma distribution with density of the form

$$\omega(r) = Ar^{\alpha}\exp(-Br^{\gamma}), \quad B = \frac{\alpha}{\gamma r_{mod}^{\gamma}},$$

is extensively used to describe droplet size in different cloud models [16–22]. Here A, α, B, γ are parameters of the distribution density of droplet concentration $\omega(r)$ in cm^3 with respect to droplet radius r in μm, and r_{mod} is the modal radius. In the Table 1 below we represent existence of glory and rainbow for several distributions used for conventional water-drop cloud models. The Table 1 is built according to the properties of the phase functions without consideration of light multiple scattering. Approximate values of angular radius of the glory, presented in the Table 1, correspond to local maxima of the phase functions for wavelength 0.7 μm (red color).

Table 1

Glory and rainbow for water and *A*-water cloud models

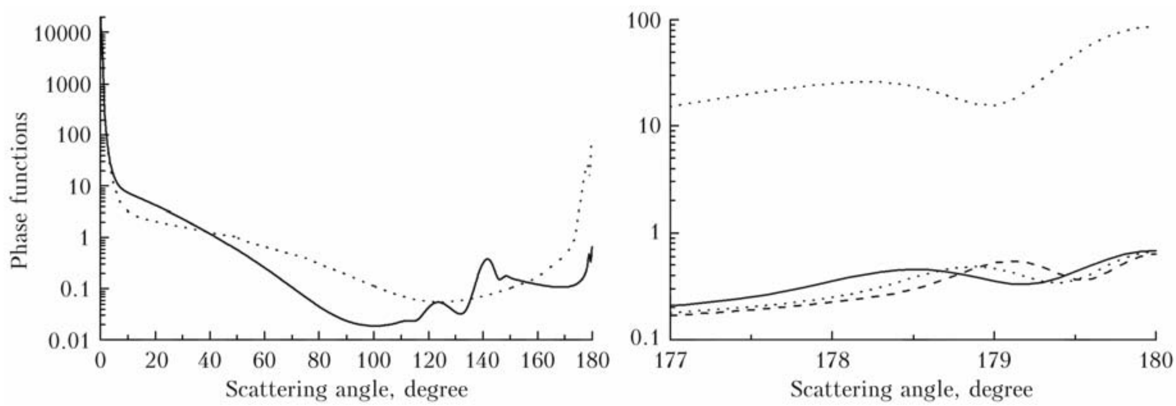
Distribution model and its parameters	Glory water / *A*-water	Rainbow water / *A*-water
Cloud *C1* [15] $\alpha = 6$, $B = 1.5$, $\gamma = 1$, $r_{mod} = 4$	Yes (3°)/No	Yes (two)/No
Cloud *C2* [15] $\alpha = 8$, $B = 0.042$, $\gamma = 3$, $r_{mod} = 4$	Yes (5°)/No	Yes (two)/No
Cloud *C3* [15] $\alpha = 8$, $B = 1/3$, $\gamma = 3$, $r_{mod} = 2$	Yes (10°)/No	Weak (white)/No
Haze *H* [15] $\alpha = 2$, $B = 20$, $\gamma = 1$, $r_{mod} = 0.1$	No/No	No/No
Haze *L* [15] $\alpha = 2$, $B = 15.2$, $\gamma = 0.5$, $r_{mod} = 0.07$	Yes (25°)/No	No/No
Haze *M* [15] $\alpha = 1$, $B = 8.94$, $\gamma = 0.5$, $r_{mod} = 0.05$	Yes (15°)/No	No/No
Advection fog, heavy [18] $\alpha = 3$, $B = 0.3$, $\gamma = 1$, $r_{mod} = 10$	Weak (< 1°)/No	Yes (two)/No
Advection fog, moderate [18] $\alpha = 3$, $B = 0.375$, $\gamma = 1$, $r_{mod} = 8$	Weak (< 2°)/No	Yes (two)/No
Radiation fog, heavy [18] $\alpha = 6$, $B = 1.5$, $\gamma = 1$, $r_{mod} = 4$	Yes (3°)/No	Yes (two)/No
Radiation fog, moderate [18] $\alpha = 6$, $B = 3$, $\gamma = 1$, $r_{mod} = 2$	Yes (5°)/No	Yes/No
Stratus, continental (OPAC) $\alpha = 5$, $B = 0.938$, $\gamma = 1.05$, $r_{mod} = 4.7$	Yes (3°)/No	Yes (two)/No
Stratus, maritime (OPAC) $\alpha = 3$, $B = 0.193$, $\gamma = 1.3$, $r_{mod} = 6.7$	Weak (< 2°)/Weak (< 3°)	Yes (two)/No
Stratocumulus (OPAC) $\alpha = 8$, $B = 0.247$, $\gamma = 2.15$, $r_{mod} = 3.5$	Yes (5°)/No	Yes (white)/No
Cumulus, continental (OPAC) $\alpha = 5$, $B = 0.0782$, $\gamma = 2.16$, $r_{mod} = 4.8$	Yes (4°)/No	Yes (two)/No
Cumulus, maritime (OPAC) $\alpha = 4$, $B = 0.00713$, $\gamma = 2.34$, $r_{mod} = 10.4$	Yes (< 2°)/Weak (< 2°)	Yes (two)/No
Stratocumulus (MODTRAN) $\alpha = 2$, $B = 0.75$, $\gamma = 1$, $r_{mod} = 2.67$	Yes (< 3°)/No	Yes (two)/No
Nimbostratus (MODTRAN) $\alpha = 2$, $B = 0.425$, $\gamma = 1$, $r_{mod} = 4.7$	No/No	Yes (two)/No
Altostratus (MODTRAN) $\alpha = 5$, $B = 1.111$, $\gamma = 1$, $r_{mod} = 4.5$	Yes (< 3°)/No	Yes (two)/No
Cumulus (MODTRAN) $\alpha = 3$, $B = 0.5$, $\gamma = 1$, $r_{mod} = 6$	Weak (< 2°)/Weak (< 3°)	Yes (two)/No

In computations we used refractive indices from [23] for water clouds and we assumed that refractive index is equal to 1.82 for *A*-water. In the Table 1, "Yes (two)" means the presence of two rainbows, "Weak" means that the local maximum of the phase function is weakly expressed, and "white" means that phase functions for the wavelengths 420, 530 and 700 nm reach local maxima at the same point. Note, that there are no *A*-water clouds among considered models with a rainbow, and only for three models a weak glory can be "observed", see Fig. 1.

Almost all water cloud models with glory produce rainbows at the same time (see, for example, Fig. 2), except models Haze *L* and Haze *M* with very fine droplets (Fig. 3).

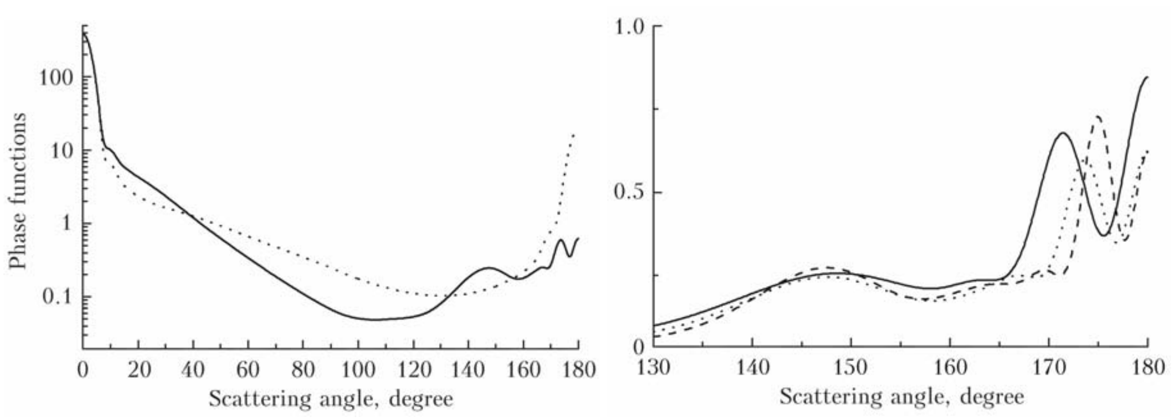
2. Glory in *A*-water clouds with normal distributions of droplet size

Phase functions for monodisperse water-drop scattering media are highly oscillating. Figuratively speaking, one could see multiple rainbows, glories, and halos if the clouds would contain droplets only of one fixed size. The oscillations of phase functions are more intensive for larger droplets. For example, using program MiePlot developed by Philip Laven, one can easily find a simple rule: a phase function for the wavelength 0.65 μm and unpolarized light has exactly $10 * X$ local maxima more or less uniformly distributed from 0 to 180 degrees if water droplet radius is equal



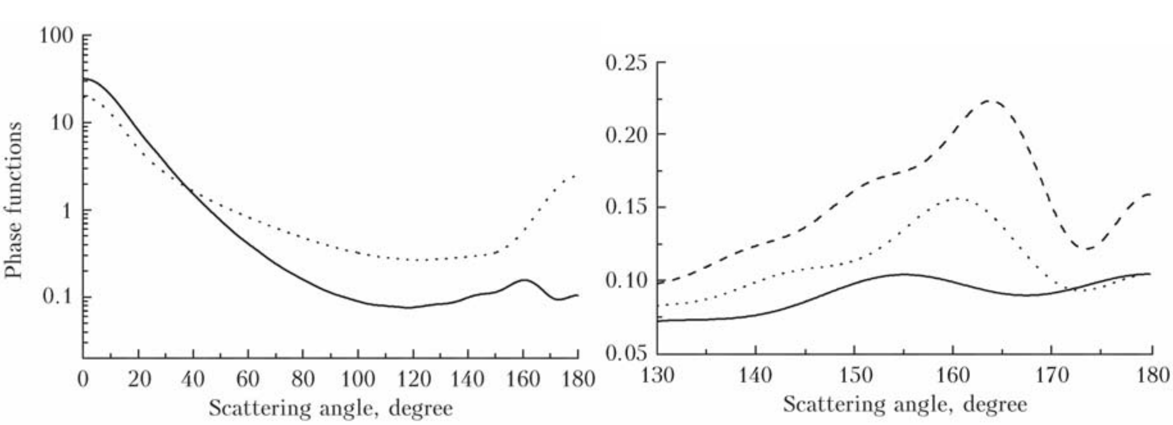
a *b*

Fig. 1. Phase functions in logarithmic scale for maritime Cumulus OPAC model of water (solid) and *A*-water (dot) clouds are presented on diagram (*a*), wavelength 530 nm. The local maxima near 120 and 140° correspond to rainbows in case of ordinary water. The phase functions for the same model of water (3 lower lines) and *A*-water (the upper line) clouds are presented for the region of glory on diagram (*b*) for wavelengths 420 nm (dash), 530 nm (dot), and 700 nm (solid)



a *b*

Fig. 2. Phase functions for *C3* model of water (solid) and *A*-water (dot) clouds are presented on diagram (*a*), wavelength 530 nm. The phase functions for the same model of water cloud are presented on diagram (*b*) for the region of glory and wavelengths 420 nm (dash), 530 nm (dot), 700 nm (solid). The local maxima near 145° correspond to a weak white rainbow in the water cloud



a *b*

Fig. 3. Phase functions of water (solid) and *A*-water (dot) Haze *L* model are on diagram (*a*), wavelength 530 nm. The phase functions for water Haze *L* model are presented for the region of glory on diagram (*b*) for wavelengths 420 nm (dash), 530 nm (dot), and 700 nm (solid)

to X μm, $X = 0.2, 0.3, ..., 2.0$ (exception is $X = 1.3$ with 14 local maxima). There are about 90 local maxima for water droplet radius 10 μm and etc. A similar behavior is typical for A-water phase functions as well. Natural continuous distributions of droplet size in clouds make real phase functions considerably smoother. We studied in detail phase functions of water and A-water clouds for Gaussian distributions of droplet radius with different average values and variances, see Tables 2, 3. Approximate values of angular radii presented in the Tables 2 and 3 for the halos, rainbows and glories correspond to local maxima of the phase functions for red color (the goal was to give qualitative representation, but not the exact values for local maxima).

Table 2

Angular radii (in degrees) of glories, rainbows, and halos for normal distributions of *A*-water droplet radius with average *M* and standard deviation σ

M, μm	σ, μm	Halo	Rainbow	Glory
1	0.05	40	35, 55	No
1	0.1	No	No	No
5	0.25	6, 10, 13	No	6, 11
5	0.5	6, 10	No	6, 12
5	1	No	No	No
10	0.5	3, 5, 7, 9	No	3, 6, 9
10	1	3, 5	No	3, 6
10	2	No	No	3
10	4	No	No	2
20	1	1.5, 2.5, 3.5, 4.5, 5.5	No	1.5, 3, 4.5, 6
20	2	1.5, 2.5	No	1.5, 3
20	4	No	No	1.5–2.5
20	8	No	No	2.5
40	2	0.8, 1.3, 1.8, 2.3, 2.8	No	0.8, 1.5, 2.2, 2.8
40	4	0.8, 1.3	No	0.8, 1.4, 2.8
40	8	No	No	0.7, 2.8
40	16	No	No	0.5, 3
80	4	0.4, 0.7, 0.9, 1.2	No	0.3, 0.7, 1.1, 2.0, 3.2
80	8	0.4	No	0.4, 0.7, 1.1, 2.0, 3.2
80	16	No	No	0.4, 2.0, 3.2
80	32	No	No	3.2

Table 3

Angular radii (in degrees) of glories, rainbows, and halos for normal distributions of water droplet radius with average *M* and standard deviation σ

M, μm	σ, μm	Halo	Rainbow	Glory
1	2	3	4	5
1	0.05	27, 47	80, 60, 40, 20	No
1	0.1	25	18, 39	No
1	0.2	No	32(weak)	16
1	0.4	No	no	13
5	0.25	6, 10, 13	35	4, 8, 12, 16, 20

Continue table 3

1	2	3	4	5
5	0.5	6, 10	35	4, 8, 12, 22
5	1	No	35	4
5	2	No	40	2.8
10	0.5	3.2, 5.3, 7.2	28, 38, 55,75	2, 4, 6, 8, 10, 12
10	1	3, 5	28, 38, 55, 75	2, 4, 6
10	2	3	28, 38, 55, 75	2
10	4	No	38, 55	1.5
20	1	1.5, 2.5, 3.5, 4.5, 5.5	25, 28, 33, 40, 55, 66, 74	1, 2, 3, 4, 5
20	2	1.5, 2.5	29, 33, 40, 55, 65	1, 2
20	4	No	33, 40, 55, 65	1
20	8	No	40, 55	0.75
40	2	0.8, 1.3, 1.8, 2.3, 2.8	31, 34, 37, 41, 53, 60, 65	0.5, 1, 1.5, 2
40	4	0.8, 1.3	31, 34, 37, 41, 53, 60, 65	0.5, 1, 1.5
40	8	No	37, 41, 53, 60	0.5
40	16	No	41, 53	No

Let us indicate some differences between phase functions for water and A-water clouds. (1) Basically, in water clouds glories are always accompanied by rainbows, while A-water clouds do not produce rainbows. (2) For the same distributions the structure of glories are rather different for water and A-water clouds, while the halos are similar, see Figs. 4, 5.

Moreover, a big difference can be found in characteristics of polarization for light scattered by water and A-water clouds. In Figs. 6, 7 we presented direction and degree of polarization for single scattering of unpolarized light. Degree of polarization was computed by formula $(Q^2 + U^2 + V^2)^{1/2}/I$, where I, Q, U, V are Stokes parameters.

3. Conclusion

In our opinion, it is of prime importance to verify Nevzorov's hypothesis about A-water. If atmospheric cold clouds contain a fair quantity of A-water, then conventional optical and microphysical cloud models should be considerably modified and many up-to-date techniques to solve direct and inverse problems of atmosphere optics, probably, must be improved. At present, after about 20 years, the A-water hypothesis is not refuted, and not well studied. One of the essential arguments [9], giving support to the hypothesis and confirmed by our computations, is that the glory for normal water clouds in most cases should be accompanied by rainbows (which is not typical for real observations). On the other hand, the idea of Anatoly Nevzorov to explain the second glory by additional scattering on ice crystals [9] seems to be excessively sophisticated. It is true that multiple scattering in ice clouds with oriented crystals "changes" angular distributions of radiation fields. In [24, 25]

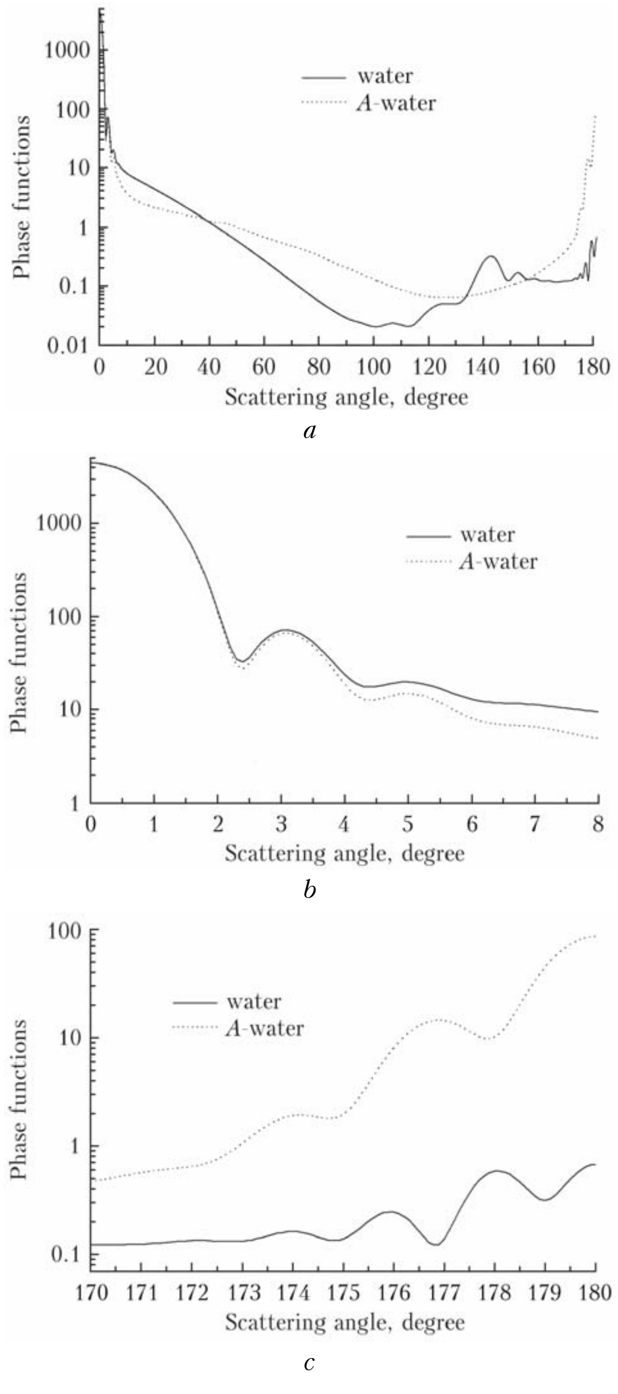


Fig. 4. Diagram (a) shows phase functions for normal distribution of water (solid) and A-water (dot) droplet radius with mean value M = 10 μm and standard deviation 1 μm, wavelength 700 nm. Diagrams (b) and (c) represent the phase functions in halo and glory regions, respectively

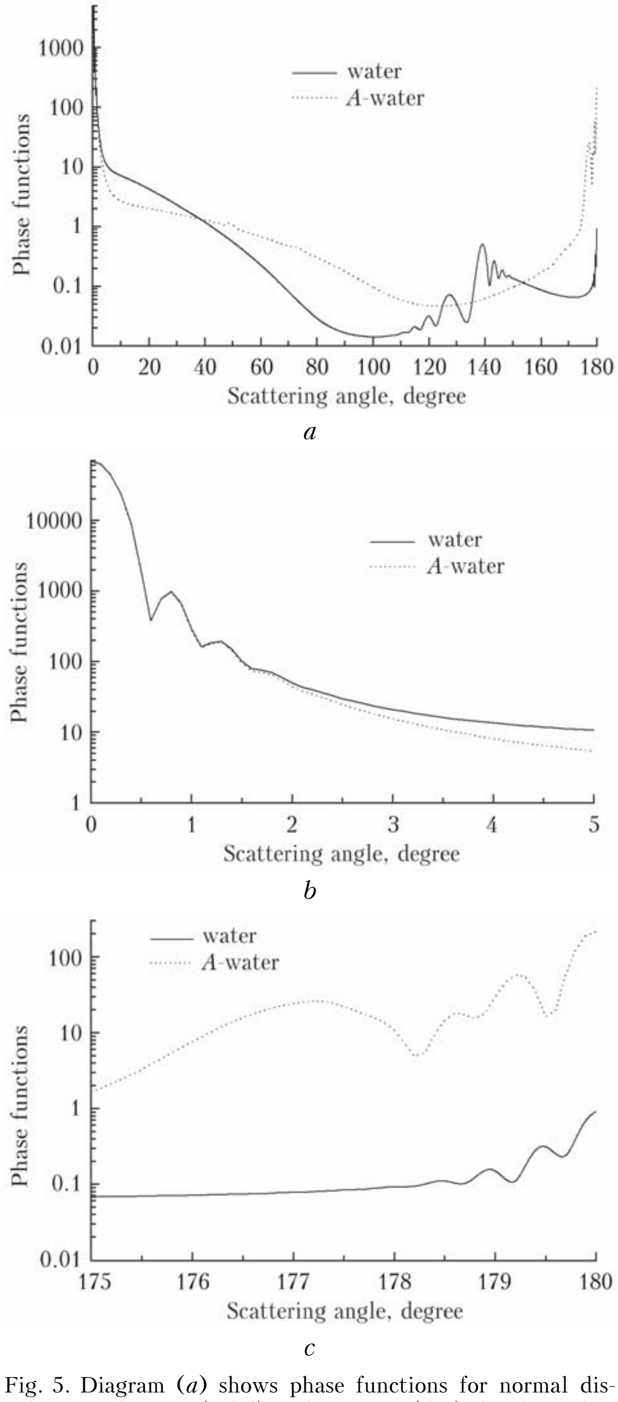


Fig. 5. Diagram (a) shows phase functions for normal distribution of water (solid) and A-water (dot) droplet radius with mean value M = 40 μm and standard deviation 4 μm, wavelength 700 nm. Diagrams (b) and (c) represent the phase functions in halo and glory regions, respectively

we studied, for instance, the impact of different scattering orders on halo formation. But in A-water clouds, the second glory can be simply explained in the framework of the Mie theory: computations showed complicated structure of the glory in A-water clouds for many distributions of droplet size (see, for example, Figs. 4, 5).

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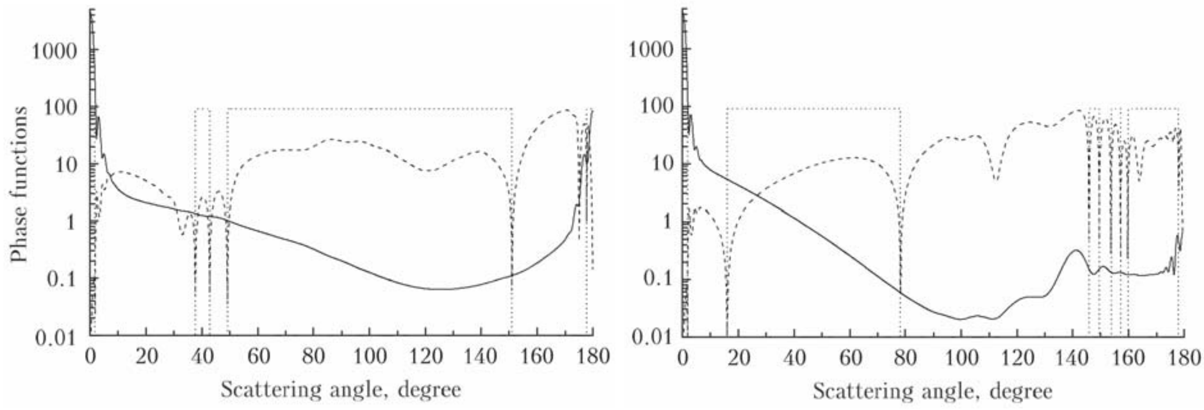

Fig. 6. Phase function (solid) and degree of polarization ×100% (dash) in logarithmic scale for Gaussian distribution of A-water (a) and water (b) droplet radius with mean value M = 10 μm and standard deviation 1 μm, wavelength 700 nm. Polarization is radial under rectangles (dot) and tangential, otherwise

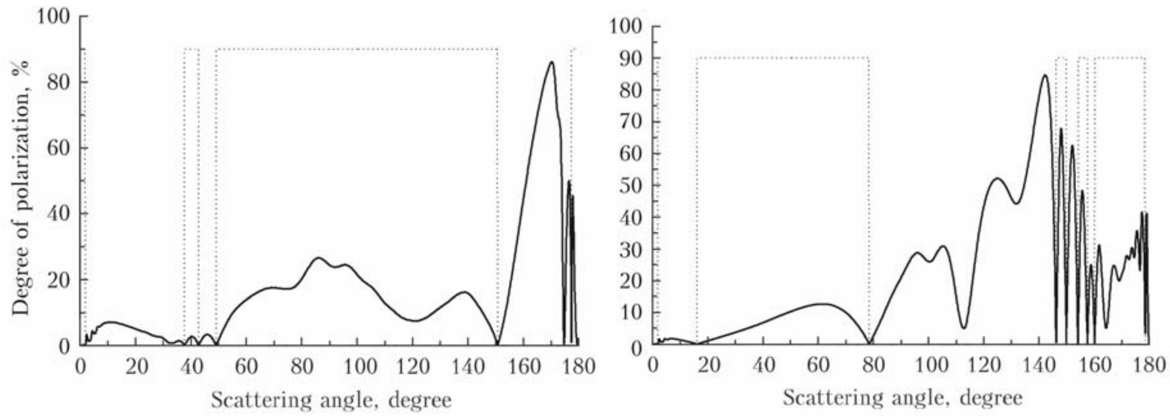

Fig. 7. Degree of polarization ×100% (from Fig. 6, but in linear scale) for Gaussian distribution of A-water (a) and water (b) droplet radius with mean value M = 10 μm and standard deviation 1 μm, wavelength 700 nm. Polarization is radial under rectangles (dot) and tangential, otherwise

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1. F. Franks (Ed.), Water and Aqueous Solutions at Subzero Temperature, Plenum Press, New York, 1982.
2. A.N. Nevzorov, Some properties of metastable states of water, Physics of Wave Phenomena. Vol. 14, No. 1. P. 45–57 (2006).
3. A.N. Nevzorov, Permanence, properties and nature of liquid phase in ice-containing clouds. 11th Int. Conf. on Clouds and Precipitation, 1992, Montreal, Canada. P. 270–273.
4. A.N. Nevzorov, Investigations in physics of liquid phase in ice-containing clouds, Meteorologiya i Gidrologiya, Vol. 18, No. 9. P. 55–68 (1993) [in Russian].
The same reference in Russian:
Невзоров А.Н. Исследования по физике жидкой фазы в льдосодержащих облаках // Метеорол. и гидрол. 1993. № 1. С. 55–68.
5. A.N. Nevzorov, Cloud phase composition and phase evolution as deduced from experimental evidence and physicochemical concepts, 13th Int. Conf. on Clouds and Precipitation, Reno, Nevada, USA. P. 728–731 (2000).
6. A.N. Nevzorov, Internal Mechanism of Metastable Liquid Water Crystallization and Its Effects on Intracloud Processes, Izvestiya RAN, Atmos. and Ocean Phys. Vol. 42, No. 6. P. 765–772 (2006).
The same reference in Russian:
Невзоров А.Н. О внутреннем механизме кристаллизации метастабильной жидкой воды и об его эффектах, влияющих на внутриоблачные процессы // Изв. РАН. Физ. атмосф. и океана. 2006. Т. 42, № 6. С. 830–838.
7. A.N. Nevzorov, Bimorphism and properties of liquid water in cold clouds, In: Some problems of cloud physics, Meteorologiya i Gidrologiya, Moscow, 2008. P. 268–298 [in Russian].
The same reference in Russian:
Невзоров А.Н. Биморфизм и свойства жидкокапельной воды в холодных облаках // Вопросы физики облаков. М.: Метеорология и гидрология, 2008. С. 268–298.
8. A.N. Nevzorov, Glory phenomenon and a nature of liquid-drop fraction in cold clouds, Atmospheric and Oceanic Optics. V. 20, No. 8. P. 613–619 (2007).

9. A.N. Nevzorov, On the theory and physics of glory formation, Atmospheric and Oceanic Optics. Vol. 24, No. 4. P. 344–348 (2011).
10. B. Mayer, C. Emde, Comment on "Glory phenomenon informs of presence and phase state of liquid water in clouds" by Anatoly N. Nevzorov, Atmospheric Research. Vol. 84. P. 410–419 (2007).
11. B. Mayer, M. Schröder, R. Preusker, and L. Shüller, Remote sensing of water cloud droplet size distribution using the backscattering glory: a case study. Atmos. Chem. Phys. Vol. 4. P. 1255–1263 (2004).
12. P. Laven, Simulation of rainbows, coronas, and glories by use of Mie theory, Appl. Opt. Vol. 42, No. 3. P. 436–444 (2003).
13. P. Laven, How are glories formed? Appl. Opt. Vol. 44, No. 27. P. 5675–5683 (2005).
14. N.P. Romanov, S.O. Dubnichenko, Physics of formation and analytical description of glory properties. Atmospheric and Oceanic Optics, Vol. 23, No. 7, P. 549–560 (2010).
15. W. Wiscombe, Improved Mie scattering algorithms, Appl. Opt., Vol. 19, No. 9. P. 1505–1509 (1980).
16. D. Deirmendjian, Electromagnetic Scattering on Spherical Polydispersions, American Elsevier, New York, 1969, 290 pp.
17. M. Hess, P. Koepke, and I. Schult, Optical properties of aerosols and clouds: the software package OPAC, Bull. Amer. Meteor. Soc. Vol. 79. P. 831–844 (1998).
18. A. Berk, L.S. Bernstein, G.P. Anderson, P.K. Acharya, D.C. Robertson, J.H. Chetwynd, and S.M. Adler-Golden, MODTRAN Cloud and Multiple Scattering Upgrades with Application to AVIRIS, Remote Sens. Environ. Vol. 65. P. 367–375 (1998).
19. E.P. Shettle and R.W. Fenn, Models for the Aerosols for the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties. AFGL-TR-79-0214 Environmental Research Papers. No. 676. 1979.
20. P.V. Dyachenko, Experimental Application of the Method of Mathematical Statistics to Microstructural Fog and Cloud Research, Voeikov Main Geophys. Obser. 1962.
21. B.A. Silverman and E.D. Sprague, Airborne measurement of in-cloud visibility, Preprints, Second National Conf. on Weather Modification, Santa Barbara, CA, Amer. Meteor. Soc. P. 271–276 (1970).
22. L.W. Abreu and G.P. Anderson, The MODTRAN 2/3 Report and LOWTRAN 7 Model, Prepared by Ontar Corporation for PL/GPOS. 1996.
23. D. Segelstein, The Complex Refractive Index of Water, M.S. Thesis, University of Missouri, Kansas City, 1981.
24. S.M. Prigarin, A.G. Borovoi, U. Oppel, Halos and multiple scattering in crystal clouds (results of Monte Carlo simulation), Proceedings of XVI Int. Sympos. "Atmospheric and Ocean Optics. Atmospheric Physics" (Tomsk, October 12–15, 2009). Tomsk: Institute of Atmospheric Optics, 2009. P. 374–377.
25. S.M. Prigarin, Numerical simulation of halo in crystal clouds by Monte Carlo method, Russian J. Numer. Anal. Math. Modelling (2009). Vol. 24, No. 5. P. 481–494.