Glory phenomenon and a nature of liquid-drop fraction in cold clouds

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Convincing evidences are obtained, that glory in classic definition is formed in clouds of negative temperature as a rainbow of first order on spherical particles with a refractive index of 1.81–1.82 and the diameter greater than 20 μm. It is proved that glory on a cold cloud is the rainbow formed on spheres with the aforementioned optical properties. New confirmation is obtained of the earlier found existence of liquid water droplets in especial state of amorphous water, or A-water, in cold clouds. The visible size of glory can be an indicator if the maximum size of the A-water droplets, and its additional rings can mean the presence of some shapes of ice crystals.

Introduction

Optical phenomenon, called the glory, is an irradiating rainbow ring around opposite-to-Sun shadow on the top of a cloud or fog. Many years ago the glory was rarely observed in mountains as a color nimbus surrounding the head of observer on the underlying fog layer ("Brocken phantom"). Today this colorful phenomenon can be often seen from aircraft (Fig. 1) and from space.

According to general idea, glory is formed due to light scattering by spherical particles, i.e., cloud droplets. As for the mechanism of its formation, no consensus of opinions and complete theory adequately describing the glory properties can be found to date. Hence, the data on microphysical structure of a cloud containing in this phenomenon is still far from understanding, therefore it remains unclaimed in problems of cloud monitoring.

It is a hardly noticeable and inexplicable fact that glory is typically observed on clouds and fogs with temperature of the top lower than 0°C, including low-temperature clouds of upper layer (cirrus) traditionally considered as a pure ice. The existence of liquid (or frozen, that does not change the general sence) droplets in such cold clouds (CC) is related to the most discussible problems of cloud physics. On the one hand, it is disputed by fundamental principles of droplet freezing and recondensation of super-cooled water to ice, but on the other hand, it is detected not as an exclusion when sampling with impactors, "graining" of cloud crystals, and so on.[22] Instrumental measurements from aircrafts allowed one to determine that liquid droplets are practically always present in CC and even at temperatures lower than -40 °C, reaching tens and hundreds of micrometers.[5,11,17] Analysis of the instrumental data has shown that some properties of liquid water in clouds, where droplets stably coexist with ice particles, significantly differ from that of super-cooled usual water, in particular, by such properties as condensation equilibrium with ice and anomalously high refractive index estimated within 1.8–1.9 [Ref. 4].

The ability of H_2O to polymorphism at negative temperatures is confirmed by numerous experiments.[6,10,12] The conclusion suggests itself that the appearance of glory in CC is directly related with the presence of droplets of polymorphous water in them, which is called A-water. This paper is devoted to confirmation of this conclusion and to the study of the relation between the properties of glory and microphysical structure of clouds. As compared to previous paper,[20] some calculation results are corrected, and the drawn conclusions are amended.

1. Properties of glory as a natural phenomenon

Insufficient attention of researchers to glory as a natural phenomenon results in a lack of information about this subject in the literature, which could clarify the relation between its characteristics and the properties of clouds. The following description of glory is based on early experimental observations generalized by Minnart,[3] observations by the author, and analysis of about 30 color pictures of glory made from aircrafts at different time. Our description is constructed so that it could be possible to connect various, at first glance, different properties of the phenomenon.

1. Rainbow glory is typically formed on clouds with temperature of the top lower than 0°C, including the clouds of the upper layer meant as pure ice. We observed from inside such a thin cloud the presence of glory simultaneously with halo and lower sun generated by ice crystals.

2. The main inherent element of glory is, most often, ideally round irradiating ring consisting of color belts smoothly changing to each other. Its geometric center is situated on the shadow projection of the observation point and is surrounded by a white aureole (Fig. 1).

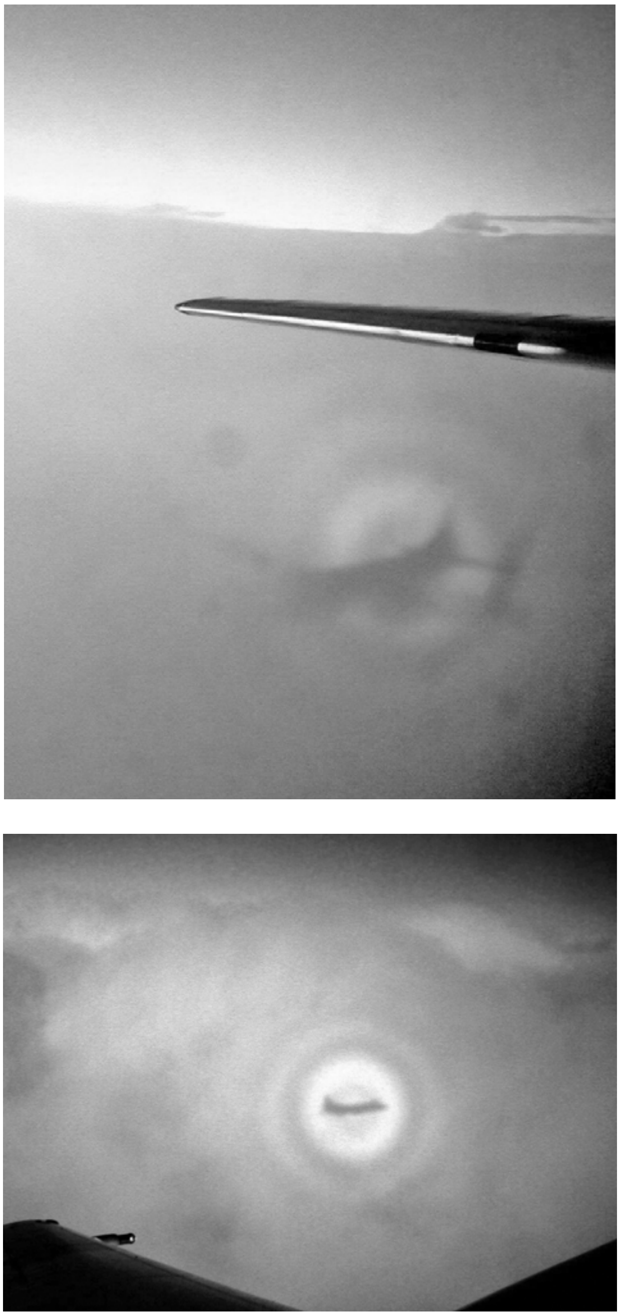

Fig. 1. Glory around the airplane shadow on cloud (picture by A.V. Korolev). Geometric center of the glory ring corresponds to the position of photocamera in the airplane.

3. Radial sequence of colors in the glory ring includes red external edge changing to orange, yellow, and finally to practically achromatic inner zone. Light throughout the ring is polarized in radial direction (i.e., positively) like in rainbow.

4. The main glory ring is often (but not always) surrounded by one to three significantly weaker rings (see Fig. 1) colored similarly to the main one.

5. Measured angular radii of the yellow zone of the main ring fall between 1.5 and 3.8°. As a rule, the greater is the glory size, the brighter is its image.

6. Such glory characteristics as visible size, brightness, and color contrast show the tendency to intensification with increasing the cloud transparency. On the contrary, the smallest, hardly noticeable and colorless glory usually appears in the densest clouds.

All aforementioned peculiarities of glory can be easily observed from an aircraft. The presented analysis of the physical nature of the phenomenon is based on these peculiarities.

2. Existing imaginations about the nature of glory

It is generally accepted as axiom that glory is the effect of light backscattering from cloud droplets. Disagreements appear only about its physical origin. Naturally, in the absence of alternative, all proposed physical interpretation of glory were related to the droplets of usual water with refractive index $n = 1.33$. Actually, the halos of backscattering radiation from warm cloud or fog were observed both in laboratory experiments[2] and in the model calculated using the Mie theory at $n \approx 1.33$ (for example, Ref. 16), which will be considered below. However, somewhat rigorously justified physical explanation of this phenomenon is still absent. The formerly popular idea of light diffraction on cloud droplets was rejected by van de Hulst[7] because of unreality of formation of a directed light beam from inside the cloud, necessary for creation of a diffraction pattern. The more convincing explanation of the phenomenon by means of surface waves [7,15] is based on speculative assumptions and therefore cannot be accepted as a final one.

There appears another question: how this virtual model corresponds to the real natural phenomenon of glory? Unfortunately, users of this model did not compare in detail their properties and did not study the microstructure of specific clouds, on which glory was observed. We try, as possible, to fill in this gap.

All author's calculations of light scattering were performed with Mie formulas and the program developed by A.G. Petrushin. They deal with individual droplets or clouds of monodispersion droplets ignoring secondary scattering. As a size characteristic of the optical pattern, formed by an ensemble of droplets in the backward direction, i.e., at $\beta > 90°$, the angle $\varphi = 180° - \beta$ of the observation from the side of the light source is used.

The angular functions of the intensity of light scattered by usual water droplets of different sizes to the angular range of φ angles characteristic of natural glory, calculated by Mie formulas, are shown in Fig. 2. The calculations were performed for three wavelength bands taking into account the wavelength dependence of the refractive index n of liquid water. Each curve contains a single peak of significant amplitude (on the contrary to damping oscillations in other known papers[15]), the angle of the top and the angular width of which depend on the size of the light-scattering droplet. According to Fig. 2, the sequence of colors in the calculation model, in principle, follows the pattern of the natural glory, but only at $n \approx 1.33$. Other formal similarities between the calculation model and the actual phenomenon characteristic of a cold cloud are absent. The following set of serious contradictions between them seems more essential:

1) the calculated peak (Fig. 2) decreases and widens with increase of the observation angle, while the natural glory shows the opposite tendency;

2) the angles characteristic of glory (from 1.5 to 3.8°) in the calculation model are related to the droplets with diameters from ~ 8 to ~ 16 μm. The clear color ring can be formed only in the cloud of practically monodispersion droplets, which is improbable in nature at the existing frequency of observations of glory;

3) our calculation results do not show additional rings identical to the rings episodically surrounding the main ring;

4) in the calculation model at $n \approx 1.33$, the light in the peaks of intensity is always polarized in the direction orthogonal to the polarization of natural glory. (All calculated data on the polarization coefficients are uniform and are not shown in plots).

Thus, the majority of details of the theoretical backscattering model at $n \approx 1.33$ are in disagreement with the glory phenomenon described above. In other words, this model describes another phenomenon different both in its properties and, obviously, in the principle of formation.

3. Glory as a rainbow

The idea of the glory origination as a rainbow with corresponding angular size is disproved by all calculations of light scattering by water ($n \approx 1.33$) and ice ($n \sim 1.31$) spherical particles. For droplets of usual water, the theory (see below) shows only the known rainbow with a radial angle of observation of about 42°. The fact that water with other properties is present in CC allows (in the essence, compels because of non-alternativeness) us to consider this version.

Visual pattern of the rainbow is formed in the observer's eye by light beams scattered by a spatial ensemble of spherical particles (droplets). The converging beams forming the rainbow outgo from an individual droplet along the cone generatrix with a certain angle at the top (rainbow angle). The set of such beams from the ensemble of particles reaches the observer at the top of the inverse cone with the same angle as is shown in Fig. 3, thus creating the ring image of enhanced brightness against the general background of scattered light. In order to be well pronounced, the rainbow should be formed in the bottom layer of the cloud with very small optical thickness. Otherwise, the beams forming the optical image will be scattered by the cloud medium.

There are two approaches to theoretical description of the rainbow properties: the approximate geometric theory and the Mie rigorous theory. Comparison of results of two independent theories between each other and with the properties of real glory can serve the criterion of truth of the proposed interpretation of its physical nature.

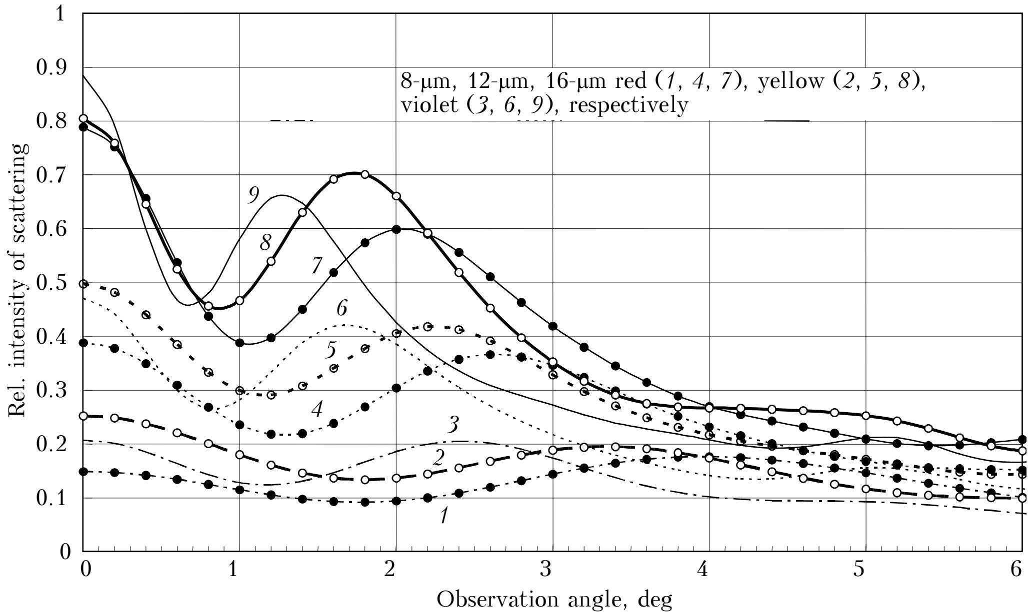

Fig. 2. Angular functions of the relative light intensity backscattered by water droplets of 8, 12, and 16 μm, for red (λ = 0.67 μm, $n = 1.328$), yellow (λ = 0.58 μm, $n = 1.334$), and violet (λ = 0.42 μm, $n = 1.340$) light. Peak of each curve determines the position of backscattering halo from the cloud of monodispersed droplets.

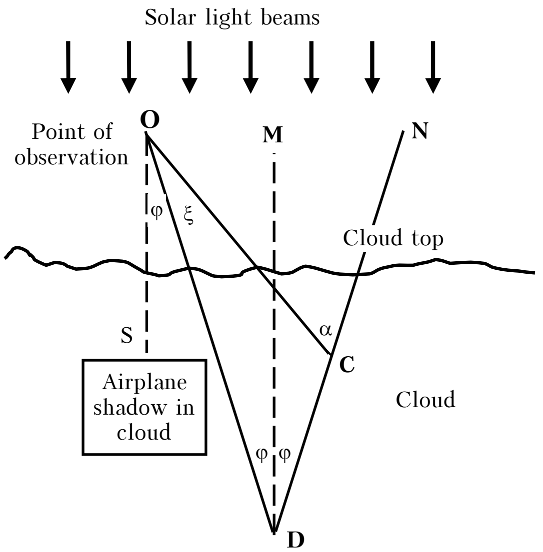

Fig. 3. Two-dimensional diagram of formation of glory image with the first secondary ring. Straight lines **OS** and **MD** are the solar light beams; **DO** and **DN** are the rainbow beams emitted by droplets located at the point **D** so that the beam **DO** penetrates to the observer's eye at the angle φ with the rainbow axis **OS** (φ = π − β, where β is the scattering angle). The line **CO** is the beam formed, evidently, by ice crystals from the rainbow beam **DN** at the halo angle α (see section 4).

Geometric theory of rainbow[8] is based on the analysis of propagation of the light beams inside some individual transparent sphere with the refractive index n, illuminated by parallel light beams. The rainbow results from the convergence of a part of beams reflected from the inner spherical surface and then outgoing from the sphere after k reflections. The total angle of turning the beams, forming the rainbow of the k-th order, is:

$$\gamma^{(k)}(n) = k\pi + 2\arcsin\frac{1}{n}\sqrt{\frac{(k+1)^2 - n^2}{(k+1)^2 - 1}} - 2(k+1)\arcsin\sqrt{\frac{(k+1)^2 - n^2}{(k+1)^2 - 1}}. \quad (1)$$

These beams go out of the particle at the scattering angle $\beta^{(k)} = \left|\gamma^{(k)} - 2\pi j\right|$, where $j \geq 0$ is the integer number providing the condition $0 < \beta^{(k)} < \pi$. Angular radius of the rainbow backscattering from the observer's eye is

$$\varphi^{(k)} = \pi - \beta^{(k)} < \pi/2\,. \quad (2)$$

Figure 4 shows the calculated dependences of the observation angles $\varphi^{(k)}$ of the backscattering rainbows from the 1-st to 7-th orders on the refractive index n of the scattering spheres. The dependence $n(\lambda)$ results in $\varphi^{(k)}(\lambda)$ represented by the spectral palette of the rainbow of each order. If, as for usual water, n increases from red to violet boundary of the visible spectrum, then the rainbow of the k-th order, described by the abating curve in Fig. 4, has the outside red zone, and the rainbow, described by the ascending curve, has the inside red zone. When estimating the reliability of the geometric approach, one can make sure that at $n \approx 1.33$ the number and angular range of the rainbows of different orders correspond to the most complete pattern of the natural rainbow.

To identify n from the angle of observation of the backscattering rainbow, it is necessary to take into account that, according to Fig. 4, the rainbow of any order $k > 1$ should be accompanied by a brighter rainbow of the 1st order. Hence, the brightest glory ring observed between 1.5 and 3.8° can belong only to the rainbow of the first order from spherical particles with a refractive index of about 1.8.

The considered geometric approximation is applicable only to rainbow angles, but it ignores the effect of the droplet size on the values of these angles due to the phase shift in the forming beams. Besides, it does not contain information on the relative intensity, angular profile, and polarization of the elementary rainbow. The Mie theory is free of these restrictions.

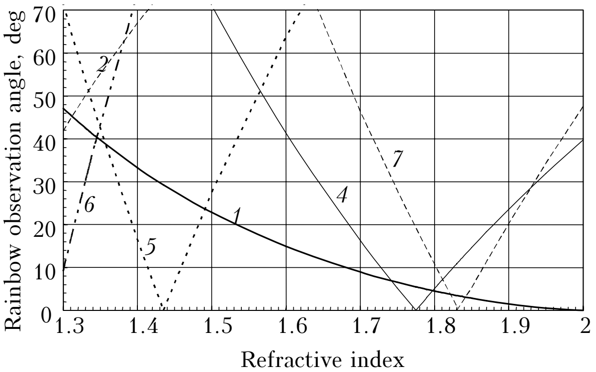

Fig. 4. Observation angles $\varphi^{(k)}$ of backscattering rainbows of different orders $k \leq 7$ as functions of the refractive index n of scattering spheres calculated by geometric theory without respect to the particle size.

Figure 5 shows the results of calculation by Mie theory of scattering phase functions in the angular range of real glory for scattering spheres of different sizes with $n = 1.81$. The well pronounced peak on the curve of the relative scattering intensity I(φ) appears, when the droplet size exceeds ~ 20 μm. As d increases, the angle of the peak top $\varphi_m(n, d)$ takes values of the glory angles, therewith the peak itself simultaneously becomes higher and narrower. The calculations also show that peaks of positive polarization, presenting against the background of the negative polarization coefficient, coincide with the peaks of the scattering intensity in Fig. 5. Note that in the range $\varphi < 90°$ other peaks, whose height and width are comparable with the aforementioned peaks, are absent on the curves of intensity and scattering polarization.

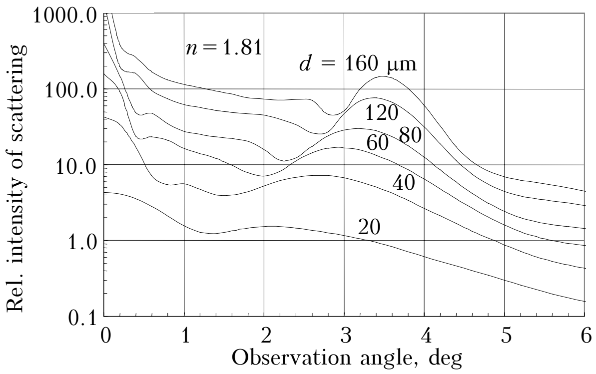

Fig. 5. Scattering phase function calculated by Mie theory at n = 1.81 and λ = 0.58 μm (yellow light), on which the peaks of intensity appear in the angular range of glory at different sizes of scattering spheres d.

Figure 6 shows the dependences of the peak angle on n at different d obtained from the curves analogous to those shown in Fig. 5. The curve $\varphi^{(1)}(n)$ calculated by the geometric theory is shown for comparison. It is easy to see that this curve is the geometric place of the asymptotes of the peak angles calculated by Mie formulas at $d \to \infty$. Such an agreement in conclusions of different independent theories means that both of them describe the same physical phenomenon of rainbow.

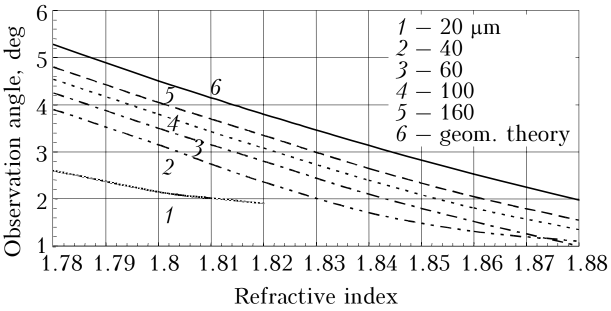

Fig. 6. Dependence of the rainbow angle $\varphi^{(1)}$ from the refractive index n obtained by Mie theory for spheres of different diameter at λ = 0.58 μm (yellow light) and, for comparison, calculated by geometric theory.

Thus, being based on the peculiarities of microstructure of CC revealed earlier (the presence of quite large droplets with $n \geq 1.8$ in clouds containing ice), the proposed calculative model of rainbow corresponds to the glory in the main characteristics (angular size range, relation between color contrast and size, polarization sign). Their difference in the color palette can be easily explained by the fact that the model is related to a monodisperse cloud illuminated by monochromatic light, while the ring width and the palette of the real pattern are determined by the droplet size spectrum width in a cloud and the spectral dispersion of natural light in droplets. The image at variations of the scattering droplet sizes is formed by mixing the polychromatic rainbows, hence, its main part, except for the external red edge, becomes mostly colorless. It is seen in Fig. 5 that the central aureole characteristic of the glory pattern (see Fig. 1) is present also in the virtual phenomenon, and its angular width weakly depends on the droplet sizes and remains white.

All aforesaid leads to the conclusion that the natural glory is the superposition of rainbows of the first order formed on polydispersion droplets of A-water contained in clouds.

The family of curves in Fig. 6 makes it possible to determine more exactly the values of the refractive index of A-water as compared to the pervious estimate n = 1.8–1.9 [Ref. 4]. As the range of angular radii of glory is limited from below by the minimal "rainbow-forming" droplet sizes (no more than 20 μm), and from above by the maximal droplet sizes in CC about hundreds of micrometers,[11] angular limits of ~ 1.5 to ~ 3.8° are most likely due to the refractive index value between 1.81 and 1.82 in yellow light.

Using the fact that the size ratio (1.20–1.25) of red and yellow zones is practically constant (within the limits of the error in their identification), it is possible to at least roughly estimate n for red light as well. Angular functions of the scattering intensity at d = 160 μm for two values of the refractive index of droplets are shown in Fig. 7: n = 1.81, approximately corresponding to yellow light for A-water, and n = 1.795 selected for conservation of the ratio between the angles of red and yellow zones. In this way, for A-water $n \sim$ 1.795–1.805 in the red spectral band.

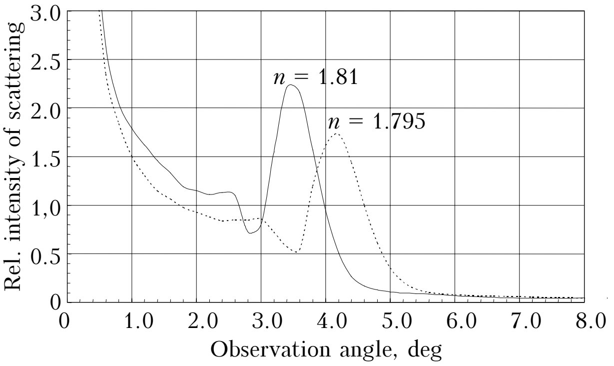

Fig. 7. The ratio of angular size of red and yellow zones of glory as a tentative estimate of the difference of refractive indices of A-water in the corresponding spectral bands.

Underline that all quantitative estimates presented here are of tentative character, because positions of red and yellow zones in the glory pattern were determined visually and, hence, with some error.

4. About additional rings and irization of clouds

As was mentioned above, the Mie theory does not reveal evident signs of rings surrounding the rainbow of the first order at $d \le 160$ μm. However, up to three additional rings can accompany natural glory. But they occur not always, and regular-periodic position of additional rings, with a color similar to the main ring, does not correspond to the calculative model of rainbow of higher orders. Since we can not describe the mechanism of the light secondary scattering by droplets, which would lead to the aforementioned effect, we postulate that additional rings of glory are the product of secondary scattering of rainbow beams by ice crystals.

The scheme of formation of additional external ring is shown in Fig. 3. In addition to direct beams DO of the rainbow formed on droplets at the scattering angle β and observed at $\varphi = \pi - \beta$, the beams scattered by cloud particles from opposite beams DN of the same rainbow reach the observer. The visible ring stands out from the scattered light background owing to the peak of the scattering intensity at the angle α characteristic of ice crystals of some types. Such peaks cause the formation of a halo with different angular radii α, sometimes observed around Sun or Moon through an optically thin cloud.[1,3]

It is seen in Fig. 3 that the angle DOC between the main and additional rings is equal to $\xi = \alpha - 2\varphi$, then the radial angle COS of the additional ring is

$$\varphi_1 = \xi + \varphi = \alpha - \varphi. \qquad (3)$$

The corresponding angle of the halo can be easily determined from the directly measured angular size:

$$\alpha = 2\varphi + \xi. \qquad (4)$$

According to measurements for the nearest (of minimum angle) additional ring, α keeps its constancy from case to case, being equal to 8.5–9°. This value practically coincides with the angle of the scattering peak forming so-called Van Boosen halo and inherent to pyramidal crystal shapes.[1] The origin of the big rings can result from a sequence of secondary scattering on such crystals. Besides, among the variety of halo angles mentioned in literature, the angles are found almost multiple to the Van Boosen halo angle. At any case, it seems that shapes of crystals forming additional glory rings are quite typical for the clouds of the upper troposphere.

It is interesting to mention one more optical phenomenon observed in the forward, on the contrary to glory, hemisphere of the sunlight scattering. It is so-called cloud irization, i.e., rainbow coloring of the cloud edges facing the Sun, or the rainbow spots on thin clouds. Such spots often appear at an angular distance of 40-5° from the Sun, they can be elongated like the circle arc and, on the contrary to the rainbow, have the red edge facing the Sun center. Calculations show that the irization spots can be the fragments of the rainbow of the 2-rd order formed on spherical particles with $n = 1.81$–1.82.

5. Discussion

Calculation by Mie theory of the light scattering phase functions of spherical particles with different refractive indices have shown that the scattering phase function peak within angular size of natural glory (the radius of yellow zone from ~1.5 to ~3.8°) can be of two origins. In the case of usual liquid water with the refractive index $n \approx 1.33$ it is a corona formed by the solar light backscattering from droplets of practically equal diameters from ~8 to ~16 μm. Clouds with such microstructure are highly improbable in nature for to provide for typical appearance of glory just on cold clouds. However, the peak of the scattering phase function in the same angular range also appears when the refractive index of scattering spherical particles falls in the range 1.81–1.82, and the particle sizes are greater than ~ 20 μm. The conclusion was drawn from comparison with independent geometric theory for the angle of convergent beam scattered by a sphere that this model is related to the rainbow of the first order formed on such particles similarly to formation of the known rainbow on the droplets of usual water. Contrary to the backscattering corona, the obtained virtual model of the rainbow reconstructs in detail all properties of the natural glory. At the same time, it was experimentally revealed earlier[4,5,18,19] that droplets with sizes significantly greater than 30 μm with anomalously high refractive index are, at least, a typical sign of clouds containing ice, on which practically always glory is observed around the aircraft solar shadow.

Thus, the presence of glory on a cold cloud means that the cloud contains liquid-droplet fraction consisting of A-water. The angular size and the width of the ring, like its photometric and color parameters, carry the unique remote information on the presence of A-water droplets in the cloud and on their size. At last, external additional rings in the total glory pattern, most likely, evidence the presence of ice crystals of specific shape in the cloud.[20]

The fact that glory is observed practically always under suitable conditions on the top of clouds containing ice phase confirms the previous conclusion that A-water is in condensation equilibrium with ice phase. The latter should mean that so-called "quasi-liquid" layer covering the surface of ice particles[13,14] practically consists of A-water, which is an intermediate stage of the Ostwald phase "jump" in transition from vapor to ice. The A-water density calculated by the Lorenz–Lorentz formula from the refractive index of water in yellow light[9] is close to 2.1 g/cm^{-3}, that is in satisfactory agreement with the most reliable measurements of the amorphous ice density,[6,10] which is about 2.3 g/cm^{-3} at ~ 100°K. Such similarity is one of the reasons to conclude that

A-water is, in physical meaning, the melt of solid amorphous condensate.[8,9] More detailed analysis of A-water and its place in the series of polymorphous states of H_2O is given if Ref. 21.

The list of physical properties of A-water known to date is given in the Table.

In our opinion, the most convincing confirmation of the concept of cloud A-water lie in the fact that it is a universal key to understanding still unsolved problems of physics of cold clouds, such as anomalous stability of the mixed phase composition of stratus clouds, super-high concentration of cloud crystals in comparison with the concentration of detectable ice-forming nuclei, the origin of so-called supercooled rain or mixed winter precipitation, and other difficult for explanation phenomena related with cold clouds. The glory phenomenon is from this series.

Table. Experimentally revealed physical properties of amorphous water

Parameter	Characteristic	Condition	Note
Softening temperature	(135 ± 1) K	$\eta = 10^{12}$ N·s·m^{-2}	1
Temperature of fluidity limit	~150 K	$\eta = 10^8$–10^9 N·s·m^{-2}	1
Dynamic viscosity η	$<10^{-2}$ N·s·m^{-2}	$T > 218$ K	1.2
Density	2.3 kg·dm^{-3}	Solid state, $T \approx 100$ K	3
	2.1 kg·dm^{-3}	Liquid state	4
Specific evaporation heat	$0.55 \cdot 10^6$ J·kg^{-1} ± 20%	$T = 243$ K	5
Latent specific heat of crystallization to ice I	$2.29 \cdot 10^6$ J·kg^{-1} ± 5%	$T = 243$ K	6
Optical shape	Transparent, colorless		1
Refractive index	1.795–1.805 1.81÷1.82	Red light yellow light	7

Notes: 1 – from Ref. 8; 2 – extrapolation of experimental dependence $\eta(T)$ from Ref. 8; 3 – from Ref. 6; 4 – calculation using refractive index; 5 – from Ref. 5; 6 – difference between the evaporation heat of ice *I* and *A*-water; 7 – this paper.

Conclusions

It is shown that the optical phenomenon of glory on clouds is the rainbow formed in scattered solar light by spherical particles larger than ~ 20 μm with a refractive index of 1.81–1.82 in yellow light. Thus, the existence of liquid water droplets in special phase state of amorphous water, or A-water, in clouds containing ice is confirmed.

We are convinced that the concept of A-water should fill the missing part in the knowledge about cold clouds, and so it deserves further study. The obtained results show that the detailed study and monitoring of the glory phenomenon are of great interest, because its appearance, as well as geometric and photochromatic parameters provide for unique remote data on the dispersion phases in cold clouds. The angular size of the glory elements can be an indicator of the particle size of A-water, and its additional rings can mean the presence of ice crystals of particular shapes.

It is not improbable that spherical particles, optically detected in stratospheric clouds of the Earth and other planets, also can consist of A-water.

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