ON A NATURE OF FORMING OF THE GLORY IN CLOUDS

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1. Introduction

The glory as classically defined is an optical phenomenon in the form of iridescent ring surrounding the observer's shadow against sunlight on a cloud top. As any cloud-formed optical phenomenon, the glory carries certain information on the cloud microstructure. Unfortunately, the information thereby offered is still far from being deciphered. Few attempts of physical interpretation of the phenomenon were based on laboratory modeling of like optical effect in a warm fog (van de Hulst, 1957), i. e. under conditions unequal to natural ones. Although today's demands and means make the glory to be objectively attractive for a careful study, no serious scientific interest in this phenomenon is actually being shown at present time. That the glory phenomenon deserves more attention of the cloud physicists may be seen from the simplest example. Namely, since it is universally recognized that the glory originates in spherical particles, it would serve for the most objective identification of mixed clouds. Its applications would be expected to extend even further.

Considered here are both a physical nature of the phenomenon and some of information therein consisted on the cloud composition.

2. Description of the phenomenon

The following description of the glory relies on the most detailed of its published descriptions given by Minnaert (1969), author's own observations, and a series of the glory photographs made from a plane. Our description is composed so that the most characteristic details of the phenomenon are selected.

(i) A basic element of the glory is a shining, rather regular ring, consisting of color circles grading into each other. Its geometrical center is positioned on the shadow projection of the observation point and is usually surrounded by a white aureole.

(ii) The radial sequence of the colors in the glory is somewhat similar to that of well-known rainbow, with the red outer edge. Light of the glory is polarized in the same direction as that of the rainbow.

(iii) In relatively rare instances, the basic ring is surrounded by one or more much weaker colored rings.

(iv) Though the existing notions of the glory relate its visible proportion with droplet sizes, no certain data on this property are widely available. Our estimations were made from the glory photographic images with the standard image of the sun disc (angular radius 0.268^{o}). The result is that the angular radius of nearly middle (yellow) circle of the basic ring varies from case to case between 1.5^{o} and 3.8^{o}.

(v) Both the visible size and the brightness of the glory have a tendency to rise with clouds being more transparent. Contrariwise, the smallest glories are scarcely discernible and pale-colored and occur in most dense clouds.

(vi) The iridescent glory is formed only in clouds having the top temperatures below 0^{o}C, including those traditionally referred to purely ice ones. The cases were met with where the glory was observed within a transparent cloud simultaneously with such ice-formed effects as the undersun and the halo.

3. Versions

Three rival hypotheses of a nature of the glory phenomenon were touched on in the literature and are to be discussed here:

- An effect of the light diffraction on cloud particles,
- A corona of the backscattering from water droplets,
- A scattering bow formed by water droplets.

The most early diffraction version has been seriously negated by van de Hulst (1957), and we cannot but subscribe to his basic arguments. At the same time, the semi-empirical theory of the back corona advanced by him as well as his criticism of the bow version need a revision in light of the modern knowledge of the cloud physics. Besides, the Mie rigorous theory of light scattering by spheres presents new resources to test former notions.

All the following data of the angular scattering function (scattering indicatrix) were computed (in terms of relative units) from the Mie formulas for the light wavelength λ = 0,575 μm (yellow color). For smoothing, the results were averaged over droplet size spectra described by the gamma-distribution of the power 10, right truncated by $2d_m$, where d_m is the modal diameter. As the characteristic droplet size, the root-mean-square diameter $d_2 \approx 1.15d_m$ is hereinafter used.

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4. Is the glory a backscattering corona?

Fig. 1 shows the angular scattering functions at angles close to 180°, calculated from the Mie theory for water droplets (refractive index n = 1,33) of different sizes. Each curve contains a peak with its top angle strongly depending on droplet size. The theory reveals no multiply rings claimed by van de Hulst. The peak angles equal to those of the glory correspond to droplet diameters from ~8 μm to ~20 μm. However, the ensuing relation between the visible size and brightness of an elementary ring is in direct opposition to that observed as for the glory phenomenon. The calculations for different $n(\lambda)$ proper to liquid water have shown that the radial sequence of the colors is identical to that of the glory but with far weaker angle dependence.

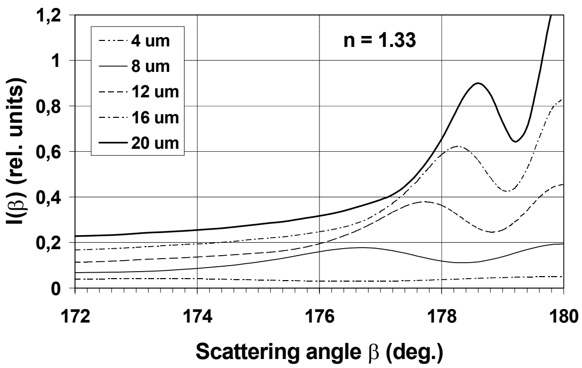

Fig. 1*. The angular functions of relative intensity of the backscattering from droplets of different sizes d_2 of the same concentrations.*

In spite of some formal similarity with the glory, the backscattering peaks produce actually different effect, namely the white aureole around the observer's shadow on the tops of warm clouds. Its corona-shaped image is possible only with very narrow droplet size spectra rather atypical of natural water clouds.

5. The glory as a bow

To refer to the bow version is caused not only by the above rejection of the rest ones. The long-known phenomenon of cloud crystal riming (Pruppacher and Klett, 1978) as well as more recent aircraft measurements (Cober et al., 1996; Mazin et al., 1992) have stated the typical presence in ice-containing clouds of liquid droplets with diameters reaching tens and hundreds micrometers. Nevzorov (1992, 1993, 2000) has found from complex microphysical measurements that the refractive index of those droplets lies between 1.8 and 1.9, and has come to a conclusion that they consist of the water in specific amorphous phase, or A - water. The idea of the bow origin from such kind of particles, capable of existing only at negative temperatures, is in agreement with the last item of the above description.

The visible bow is an image constructed in the observer's eye by certain light rays coming directly from a great number of space-dissipated individual droplets. In reality, observable are the bows formed among the back-scattered light, hence facing both the observer and the light source. The geometrical theory of the bow is presented e.g. by Shifrin (1983). The bow is considered to result from convergence of light rays entering a sphere with the refractive index n from a parallel beam and then leaving it after k internal reflections. The total angle of the turn of the rays forming the k-order bow can be expressed as

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

where

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

These rays leave a particle at the angle with the original direction (scattering angle) equal to

$$\beta^{(k)} = \left|\gamma^{(k)} - 2\pi \cdot j\right| . \quad (3)$$

Here $j \geq 0$ is such integer that provides the condition $0 < \beta^{(k)} < \pi$.

As applied to the bow as a visual phenomenon, hereinafter its visible angular radius, or observation angle φ will be used instead of the scattering angle $\beta > \pi/2$:

$$\varphi^{(k)} = \pi - \beta^{(k)} < \pi/2 . \quad (4)$$

In case when the dependence $n(\lambda)$ takes place, this results in the dependence $\varphi^{(k)}(\lambda)$ and thereby in the color palette of the bows of all orders.

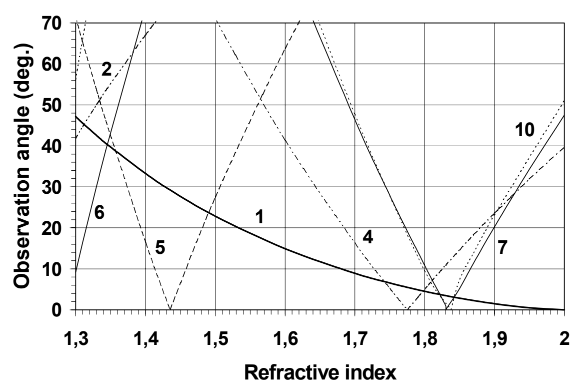

Fig. 2*. Observation angles $\varphi^{(k)}$ of the bows of different orders k (numerals by the curves) against the droplet refractive index n as calculated from the geometrical theory irrespective to droplet size.*

The observation angles of the bows of orders of 1 to 10, calculated from Eqs. (1) – (4), are plotted in Fig. 2 against the refractive index n of scattering spheres. As a support of these theoretical results, at n = 1,33 the mutual angular arrangement of the bows of different orders corresponds to the most complete picture of usual natural rainbow. Thus, the rainbow as a whole consists of four elementary bows of the orders 1, 2, 5, 6.

According to the theoretical results represented in Fig. 2, the actual angle range of the glory (from 1.5^o to 3.8^o) corresponds to the first order bow from spheres with the refractive index exceeding 1.8. The theory also predicts nearby additional bows of orders 4, 7 and 10. However, all estimations hence issued need corrections for a difference of wave phases of interfering rays, ignored by the geometrical approach. This factor is allowed for by the Mie rigorous theory.

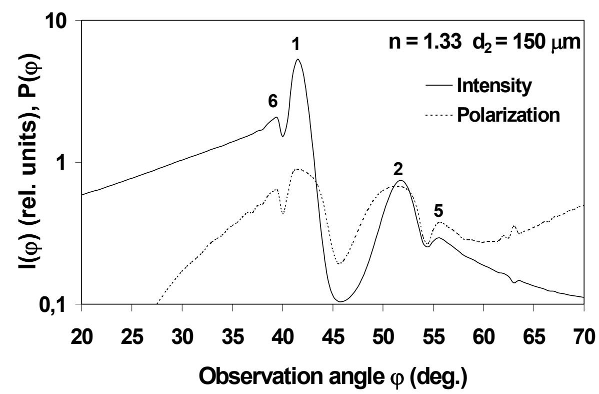

Fig. 3. *Angular scattering functions of water droplets with d_2 = 150 μm over the range of the rainbow. The numbers by the peaks denote the bow orders.*

To illustrate the reliability of the Mie tool, let us refer again to the example of the rainbow. Fig. 3 represents the angular functions of the intensity, $I(\varphi)$, and of the polarization factor, $P(\varphi)$, of light scattered by the droplets of ordinary water (n = 1,33) with d_2 = 150 μm. The curves exhibit the presence of four distinct peaks corresponding to all bows mapped in Fig. 2, but with angles displaced from their positions in Fig. 2 by ~1^o for k = 1 up to 9^o for k = 6. These differences increase with droplet size decreasing.

A review of the angular scattering functions calculated at 1.8 < n < 1.9 for d_2 ranging from 4 to 150 μm shows that as d_2 increases, a peak in each curve arises and then becomes higher and narrower as demonstrated in Fig. 4. Its top angle $\varphi_m(n,d_2)$ is at first displaced by ~2^o from the curve $\varphi^{(1)}(n)$ of Fig. 2, approaching to this with d_2 increasing.

In Fig. 5 plotted are the curves $\varphi_m(n)$ for different d_2, derived from the curve sets $I(n,\varphi)$ as in Fig. 4. One can see that the "geometrical" curve $\varphi^{(1)}(n)$, also represented in Fig. 5, is the locus of the asymptotes of the peaks angles at $d \rightarrow \infty$.

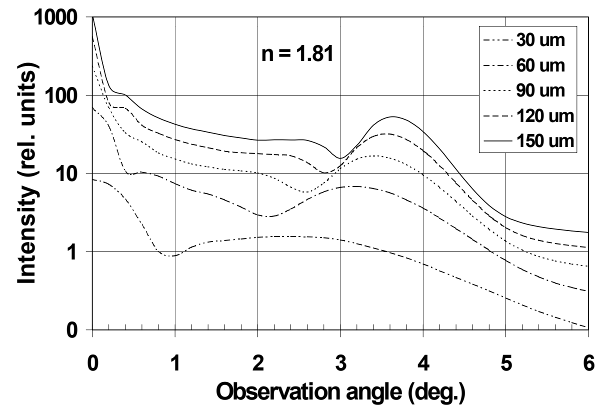

Fig. 4. *Deformation of the light scattering peak forming the bow with the droplet size d_2 changing.*

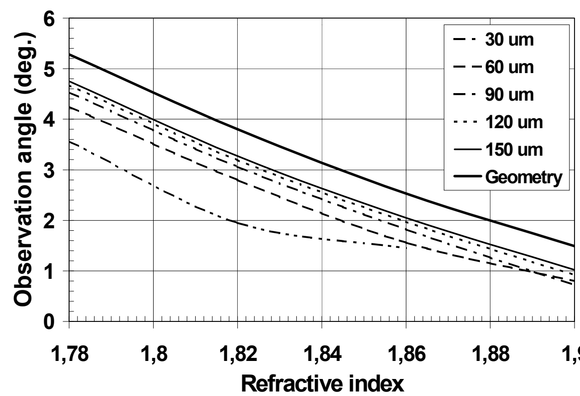

Fig. 5. *The bow angle $\varphi^{(1)}$ against the refractive index n calculated from the Mie theory at different droplet sizes d_2 and received from the geometrical theory.*

Thus, there is sufficient reason to conclude that the glory (by its classical definition) is the bow formed by spheres with the reflective index much higher than that of the ordinary water. Such spheres existing in cold clouds can be only the droplets consisting of A-water. The Mie theory affirms that both brightness and color contrast of the glory depend directly on sizes of scattering droplets. It can be seen from Fig. 4 that with droplets smaller than 150 μm, the peaks are as wide as comparable with the width of the glory ring. Therefore, the most luminous and sharply multicolored glory can be formed by substantially larger droplets. That such droplets can really occur in cold clouds is certified by Cober et al. (1996) who reported of freezing drizzle droplets reaching almost 0.5 mm in diameter.

Considering all above, one can conclude from Fig. 5 that the natural glories seen at 1.5^o to 3.8^o radial angle are produced by spheres larger than ~20 μm in diameter with the refractive index lying between 1.81 and 1.82 for the yellow color.

Fig. 4 illustrates the angular functions of intensity around the 1-order bow formed by differently sized droplets with n = 1.81. The width of the glory ring is determined both by the slope of the dependence of the refractive index on the light wavelength and by the width of the droplet size spectrum. In case of wide enough spectra, different colors are mixed within the ring so that its most part other than the red outer edge can look little or not multicolored. One can see that the central aureole is always present in the glory picture, with its width rather weakly depending on droplet sizes.

All attempts have failed to find quite evident signs of the bows of higher orders like those in Fig. 3. This is probably because of smallness of their peaks at $d_2 \leq 150$ μm, or they are so replaced from the position as in Fig. 2 that practically fuse with the central aureole or with the 1-order bow. It is difficult to assume that almost equidistant extra rings surrounding but a part of real glories are the 4-order and 7-order bows formed by substantially bigger droplets. The explanation seems to be more reasonable that they are produced by ice crystals scattering those bow rays that are diametrally opposite to the rays coming directly to the observer. The visible rings stand out against the background-scattered light due to the scattering intensity peaks at definite angles, inherent in ice crystals. The simplest analysis shows that the first extra ring is a possibility when the peak angle is $8^o \div 9^o$. In fact, such peak angle responsible for so-called Van Buijsen halo is peculiar to some pyramid-like crystal forms (Volkovitsky et al., 1980). The following rings must be results of consecutive scattering steps to be yet understood.

It is interesting that as calculated from Eqs. (1) – (3), at $n \approx 1.81 \div 1.82$ the forward directed bows of orders 2, 3, 5, 6, 8 and 9 are concentrated between the scattering angles $\sim 40^o$ and $\sim 70^o$. We believe that such forward bows of least orders are responsible for the effect of irisation of side edges of high clouds exposed to the sunlight, as occurs to be seen from the ground.

6. Conclusion

Presented in this paper are the solutions of two interrelated problems, each of its own significance:

- The optical phenomenon of the iridescent glory is proved to be the bow formed from sunlight rays scattered by spherical particles having the refractive index of 1.81 ÷ 1.82 (for yellow color) and sizes exceeding ~20 μm.
- The convincing corroboration is thereby gained of the existence in cold clouds of liquid water of special phase state, differing in physical properties from the ordinary water and discovered earlier under the term amorphous water, or A-water.

The results here obtained point out that the detailed study of the glory phenomenon is worthy of great interest of the cloud physics, inasmuch as its presences itself as well as its geometrical and photo-chromatic characteristics carry an unique remote information on the phase composition of cold clouds. In particular, the glory observation angle can serve as an indicator of the extent of the right wing of droplet size spectrum.

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