Demonstration of the light scattering phenomenon in the atmosphere

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ABSTRACT

Some phenomena of color and light in the human life and Nature are demonstrated for students in junior high and senior high school as well as college students as atmospheric optics. We used simple experiments and computer simulations as teaching materials and demonstrated atmospheric optics phenomenon so far. We let college students make computer programs in addition to experiments and computer graphics for their understanding of theory. In any case we stimulate their curiosity. It is necessary and important to let them interested in the teaching materials.

Keywords: Mie Scattering, Rayleigh scattering, Blue sky, Evening glow, Rainbow, Fog, Computer simulation, Raytracing

1. INTRODUCTION

The various optical phenomena in the atmosphere, such as rainbow, sky blue and evening glow, have captivated our poetic imagination. A lot of people see the sky with beautiful colors and some are struck with awe. Some people take them even as an object of religious belief, too. The sky was also the object of scientific study from old ages. Dietrich noticed and experimented on shapes and colors of rainbow in 1304. The mechanism of occurrence of rainbow was studied by Descartes using geometric optics such as Snell's law and refractive law. Relation between color and refractive index were discussed by Newton. This research was the first result that described colors and refractive index[1].

At school, students are strongly interested in beautiful colors in nature. They learn about colors in some classes, which are not limited to science but concerned with other subjects such as art. Outside a classroom, a color is not limited to nature, and there are artifacts in various places. Especially, they are surrounded by naturally occurring optical phenomena in their everyday lives. It means that the optical phenomena in the atmosphere are suitable for teaching materials for students.

In this study, we show students experimentally and computationally the nature of colors in the atmosphere that are caused by light scattering phenomena. Phenomena of visible colors in the atmosphere are caused by dispersion relation. To explain dispersion, our demonstration is divided into these parts, to reproduce a phenomenon, to confirm a principle, and to simulate with ray tracing.

There are sky blue and evening glow as optical phenomena around us. Demonstrations of these phenomena are simple but can impress students deeply. On the other hand, one of the most impressive phenomena on atmospheric optics is rainbow, which is caused by the dispersion of the scattered light from water droplets. We demonstrate rainbow colors using white light in several ways. We do some experiments about solar color and form such as green flash, blue sun, distortion by refraction of a light source. At the same time, a phenomenon that colors are mixed into white, such as light that go through fog, also seems to be interesting to students. We demonstrate this phenomenon of multiple scattering using small glass spheres like beads, and also explain it schematically. Besides, computer-generated graphics can give an image for a real phenomenon.

2. OPTICAL PHENOMENA IN THE ATMOSPHERE

Optical phenomena in the atmosphere are explained by the various mechanisms such as the reflection, the refraction, scattering and absorbing. Especially, the colors which are seen in the sky are caused by scattering of the white sunlight from molecule, water drops, and dust in the atmosphere[2, 3]. Intensity of scattering light depends on a ratio of

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scatterer size to wavelength of incident light. Therefore wavelength of scattering light is selected by scatterer. Besides, actually, spectrum distribution of sunlight is weak relatively in short-wavelength light such as purple since it is not uniform distribution. Furthermore, purple spectrum is scattered many times when it goes through the stratum of atmosphere and becomes weak. As a result, optical phenomena of purple in the sky can hardly be seen. There are aerosol and water drops, which are bigger scatterers than a molecule, and scattering by these materials has not a little influence near the ground in the atmosphere. Colors in the sky are decided by the various factors mentioned above. When we think about a problem of color in the atmosphere occurring by light scattering theoretically, it is necessary to use Mie's scattering theory, and to think about the phenomenon.

We describe the scattering formulation that is a factor to select a color in the atmosphere in this section. Light Scattering by particles in the atmosphere is described by Mie theory. Mie applied the Maxwell's formula to globular particle and got the following answer[2]. Namely, scattering of a natural light with plane wave and unit intensity by an isotropic, homogeneous sphere of radius a is strictly described. Light scattering intensity I_θ at a place of distance R, scattering angle θ from a particle is expressed as follows, on the condition that $R >> a$ is concluded and, scattering angle is an angle for a progress direction of incident light:

$$I_\theta = \frac{\lambda^2}{8\pi^2 R^2}\left(i_1 + i_2\right), \tag{1}$$

where

$$i_1 = \left|\sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)}\{a_n\pi_n + b_n\tau_n\}\right|^2, \qquad i_2 = \left|\sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)}\{b_n\pi_n + a_n\tau_n\}\right|^2, \tag{2}$$

$$a_n = \frac{S_n'(\beta)S_n(\alpha) - mS_n'(\alpha)S_n(\beta)}{S_n'(\beta)\Phi_n(\alpha) - m\Phi_n'(\alpha)S_n(\beta)}, \qquad b_n = \frac{mS_n'(\beta)S_n(\alpha) - S_n'(\alpha)S_n(\beta)}{mS_n'(\beta)\Phi_n(\alpha) - \Phi_n'(\alpha)S_n(\beta)}, \tag{3}$$

$$S_n(\alpha) = \sqrt{\frac{\pi\alpha}{2}} J_{n+1/2}(\alpha), \qquad C_n(\alpha) = (-1)^n \sqrt{\frac{\pi\alpha}{2}} J_{-(n+1/2)}(\alpha), \qquad \Phi_n(\alpha) = S_n(\alpha) + iC_n(\alpha), \tag{4}$$

$$\pi_n = \frac{1}{\sin\theta} P_n^{(1)}(\cos\theta), \qquad \tau_n = \frac{\partial}{\partial\theta} P_n^{(1)}(\cos\theta). \tag{5}$$

For generality of above equation, we defined following parameter and use them as fundamental factors of scattering:

$$\lambda = \lambda_0/\mu_1, \quad m = \mu_2/\mu_1, \quad \alpha = 2\pi a/\lambda, \quad \beta = m\alpha,$$

where μ_1 and μ_2 are refractive index of the medium and particles and λ and λ_0 are wavelength of light in the medium and particles, respectively.

When we describe the mechanism of sky blue, we think that the scatterers are molecule in the atmosphere. Then we can think that the size parameter is very small, namely, $\alpha << 1$ on eq.1. In this case eq.1 will be approximate to this form:

$$I_\theta = \frac{8\pi^4 a^6}{R^2\lambda^4}\left|\frac{m^2-1}{m^2+2}\right|^2\left(1+\cos^2\theta\right). \tag{6}$$

This equation is called Rayleigh scattering formulation and experimentally derived by Rayleigh. Equation 6 indicate that scattered intensity of the Rayleigh scattering is inversely proportional to the fourth power of the wavelength:

$$I_\theta \propto \frac{1}{\lambda^4}. \tag{7}$$

This equation describes that the scattering intensity depends on wavelength of incident light. In other words, the scattering by a small particle which seems to be Rayleigh scattering, the light of short wavelength is scattered more effectively than the light of long wavelength. With eq.7, we can explain the mechanism of blue sky. In addition, evening glow can also be explained with the same mechanism. Figure 1 shows the relation between an angle of incident light and thickness of the atmosphere[3]. In position A, the sun is near to the zenith, and optical path in the atmosphere is short. At such a place, with a small quantity of scattering of short wavelength sunlight, the sun looks white. On the other hand, position C shows the sun early in the morning or in the evening, therefore optical path in the atmosphere gets longer. If optical path length is long, sunlight with short wavelength scatters by Rayleigh scattering by an atmospheric molecule so that we see red sunlight. In addition, it is the mechanism that a solar color changes by time. It is expected that the red sunlight gets more brilliant when you observe a sunset at high altitudes in the atmosphere.

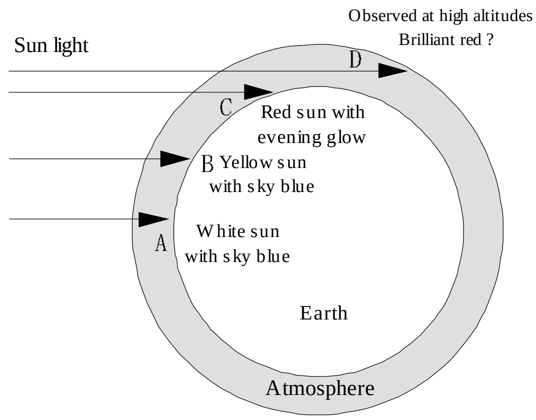

Figure 1. Relation of optical path length with the color of sky and sun.

When we think about optical phenomena of atmosphere exactly, we have to use Mie's scattering theory. However, there are some cases to be understood more easily if we use geometrical optics (law of reflection and law of refraction). As for the following phenomena, you can understand the outbreak mechanism with geometrical optics. Rainbow to be seen after rain is a well-known phenomenon. The outbreak mechanism is explained enough with geometrical optics. Figure 2 is a trace of an internal and external ray of a water drop for reproduction of rainbow. When light is incident on a drop of water, it is refracted in a drop of water and on an interface of air. The incident light that goes straight in a drop of water reflects on an interface of air. The reflected light moves in the water drop and part of it goes out, being refracted on another interface. That is, until it goes out of the drop of water, light is refracted twice and reflected once. A refractive index of water depends on wavelength of light and changes.(see table 1). This relation is called the dispersion relation. Here we mean the word of dispersion for the dependence of light behavior on wavelength. Then we call wavelength selection by scattering dispersion. Because of wavelength's dependence on a refractive index, optical path in a drop of water depends on wavelength. As a result, colors of rainbow occur because an outgoing radiation angle varies depending on wavelength.

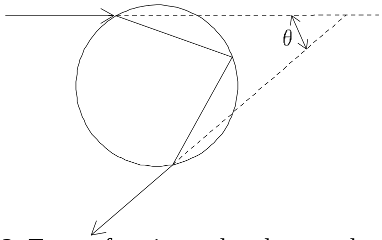

Figure2. Trace of an internal and external ray of a water drop for rainbow.

Wavelength	Refractive index	Angle θ
404.7	1.3428	40.674
546.1	1.3345	41.860
589.3	1.3330	42.078
656.3	1.3311	42.355

Table 1. Relation among wavelength, refractive index and return angle θ.

Scatterer in the atmosphere is not only a molecule and water drops but also crystallization of ice[4]. An atmospheric optics phenomenon caused by ice includes halo, parhelia, paranthelic arc and Coronae. (Coronae also occurs in a drop of water. However, there is no difference between both cases of ice and a water drop in that it occurs by diffraction.) Halo, parhelia, and paranthelic arc occur by reflection on interface of air and ice. Figure 3 shows optical path of incident light for halo in ice geometrically. Incident light shows complicated behavior in crystallization of ice because of its special shape of hexagon. As a result, patterns of complicated light such as halo, parhelia and paranthelic arc appear around the sun.

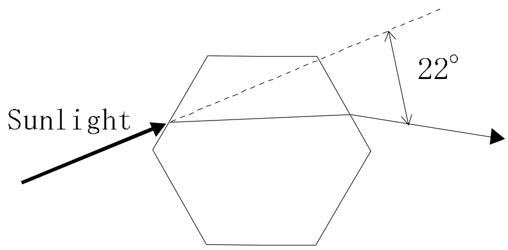

Figure 3. Schematic diagram of optical path for halo in crystallization of ice.

We can classify atmospheric optics phenomena according to a direction of scattering light. As for Halo and Coronae, scattered light takes a direction almost the same as incident light (Forward scattering). On the other hand, scattered light returns to the opposite direction of incident light about rainbow and Glory (Back scattering). We show a relation between atmospheric optics phenomena and directions of scattering in table 2.

Table 2. Relation between directions of scattering with atmospheric optical phenomena.

Direction of scattering	Forward	Backward
Phenomena	Halo (ice) Parhelia (ice) Coronae (water, ice)	Second rainbow (water) Main rainbow (water) Glory (water)

3. SIMPLE EXPERIMENTS

3.1.1 SKY BLUE AND EVENING GLOW

Colors in the atmosphere, such as sky blue and evening glow, are optical phenomena in the atmosphere, which are familiar to us. As mentioned above, the light of short wavelength is scattered much more than that of longer wavelength. As a result, the color of sky will be blue. On the other hand, the light transmitted without being scattered has longer wavelength, thus it looks red. Actually a phenomenon of colors of sky is decided by various elements. However, the mechanism of sky blue and evening glow can be explained with Rayleigh scattering. In this section, we demonstrate the phenomena of sky blue and evening glow, which is based just on Rayleigh scattering.

We prepare solution by scatterer of the size that a Rayleigh scattering approximation holds water for optical path length here. Then we show that the light of short wavelength is scattered more greatly than the light of long wavelength. As a result, the light of long wavelength transmits in the solution[3, 6, 7].

At first we put water in a big water tank and put acrylic emulsion (particle size 80nm) by degrees in it. We project a ray of incident light on this water tank like a figure and stir water in the water tank well. A trace of a ray changes in color when we thicken solution. We pay attention to the change. First we can observe the ray to be blue, and then it becomes yellow in a far-off part from the light source. The yellow part extends toward the light source as we thicken the solution. Furthermore it takes a tinge of red on the other side of the light source. Quantity of the solution which we put in a water tank applies to optical thickness of atmosphere. Therefore, the light of short wavelength is scattered and the light of longer wavelength remains as atmosphere thickens in this experiment. In addition, yellow, orange, red can be observed changing as we thicken solution when we observe a state of transmitted light.

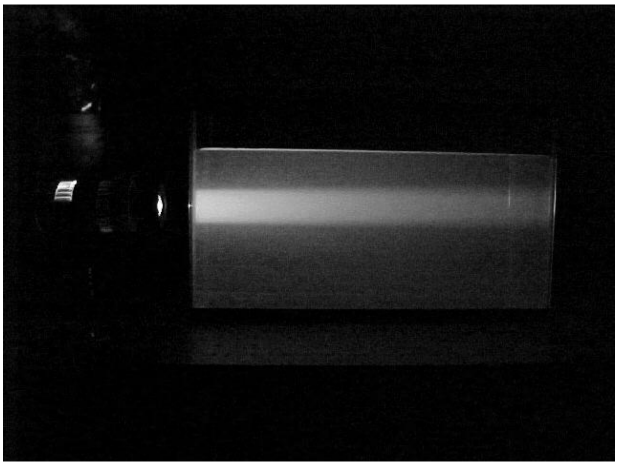

Figure 4. Demonstration of the light scattering by small particles (experiment of sunset). Ray from the electric light is put in the water tank filled with solution of fine particles.

We can disturb optical path around transmitted light by putting scatterer in a water tank. Acrylic emulsion is suitable as scatterer, though any particles available can be used.

3.2 RAINBOW

There are not many opportunities to watch rainbow, but it is interesting for people to see beautiful rainbow. In fact, a method to reproduce rainbow artificially is very simple. We demonstrate rainbow by using Rainbow beads (Nakamura Scientific Co. Ltd.) projecting electric light on them.

We make a layer of beads ball on a black screen and consider this to be water drops in the atmosphere and generate rainbow by light scattering[5].

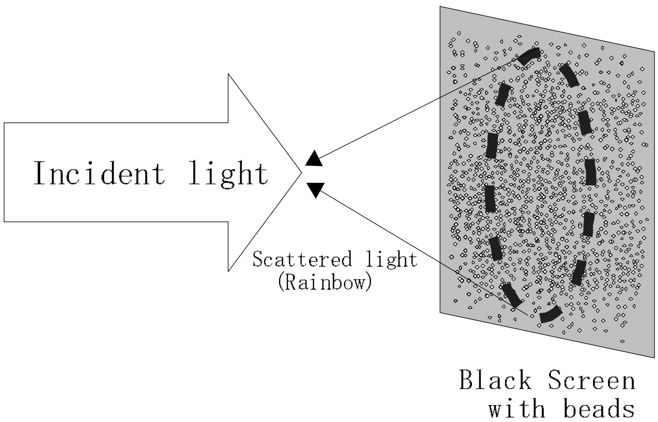

Figure 5. Schematic diagram for demonstration of rainbow using spherical beads.

Another characteristic of an experiment about rainbow is polarization. Because a reflection angle of light in a water drop is close to Brewster angle about real rainbow, scattered light is polarized[8]. The polarization of rainbow is up to 94%. However, scatterer is not a water drop in this experiment. Therefore, it is difficult to confirm polarization of rainbow by this experiment.

If it is outdoors, it is possible that we use the water and reproduce a principle of real rainbow. It is better to reproduce rainbow in fine weather. In the case, we spray the water with the sun behind us. The sunlight is scattered by the spray, and rainbow occurs. We can confirm polarized light of rainbow. The polarization of scattered light is the plane polarization, which is perpendicular polarization. When we watch rainbow through polarizing plate, we can observe rainbow when we turn a polarizing plate according to perpendicular polarized light. However, most of the rainbow light disappears when we turn the polarizing plate by 90°.

3.3 OPTICS IN FOG

When we compare the behavior of light in fog with other phenomena from a point of view of scattering, it will be characteristic. In particular, for people living in the district where fog occurs a lot, fog is an object of great concern. As for light in fog, there are phenomena regarded as multiple scattering. By multiple scattering in fog, additive color mixture of light is generated, and therefore light that go through fog looks white. We explain the reason as follows.

Like a figure, we think that fog is structure of multilayer formation with single scattering in each layer. In one layer, the behavior of scattered light depends on the shape and distribution of scatterer. But the scattered light shows a complicated aspect when it goes through multilayer. That is, it is changed into white because the light has only average information. Of course the problem is complicated so that actually there are parameters such as absorption of light.

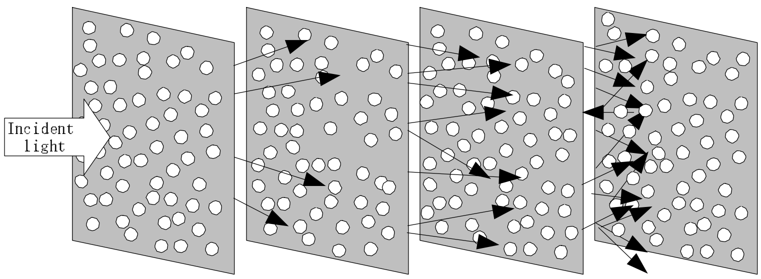

Figure 6. A stratified formation model of multiple scattering. Additive color mixture of light rises by multiple scattering.

In the experiment, we use Rainbow beads, which we used in the rainbow experiment stated above. We prepare several pieces of transparent acrylic boards pasting up Rainbow beads. We observe outdoor scenery and an indoor state through these boards just like through natural fog.

3.4 OTHER IMPRESSIVE PHENOMENA

There are a lot of strange phenomena about solar color and form. Because these phenomena are greatly different from common sense, they are fit for teaching materials for students.

Green flash, which gives people a mysterious impression, is an extremely rare phenomenon seen in the sunlight. There are many studies including a description about Green flash[7, 9].

An experiment to reproduce Green flash is as follows. Like a figure 7, we put a mirror in a water tank and adjust it so that we can observe the light from a light source. We fill a water tank with thin solution of acrylic emulsion (particle size 80nm). We project the light on the mirror in a water tank and observe the light reflected on the mirror. The reflected light becomes red by Rayleigh scattering. However, a part of the reflected light looks green.

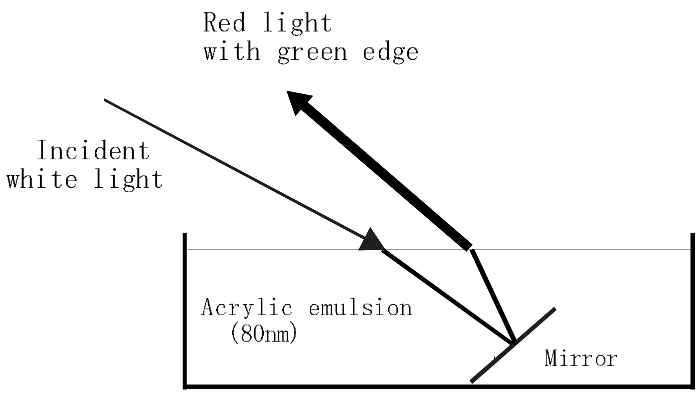

Figure 7. Schematic diagram of demonstration of green flash.

In comparison with above-mentioned Green flash, a blue sun is a phenomenon depending greatly on wavelength-selectivity of light scattering[10]. This phenomenon is seldom observed and very important all the more because it is against common sense in our everyday life.

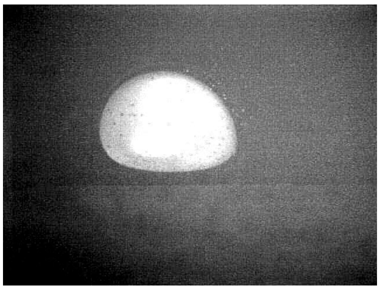

Figure 8. Distortions of Lamp image.

As for a phenomenon by refraction, you observe a change of the form as well as a change of the color. We put sugar in a bottom of a water tank and pour flesh water on it. We irradiate the light of a lamp on the water tank from the side lines[6]. An image of a round lamplight is warped by refraction (Figure 8). The light from a low part of the lamp is distorted in the solution of sugar before it reaches your eyes.

4. RAYTRACING

We usually see a real atmospheric optics phenomenon in various places by accident. Since we can seldom see such a phenomenon whenever we want to see, it is hard to use it as the teaching materials. If we cannot associate a real phenomenon when we do the above-mentioned experiment, it makes little sense except that it is beautiful in colors. There is a method of using computer graphics (CG) as one of the techniques to let you imagine a real phenomenon at same time. We use CG by rendering software (raytracing) and computer simulation of our own making in order to link a theory and an experiment to a real phenomenon.

When you understand a principle of a natural phenomenon, it is useful to use computer simulation in the following points.

1. We can illustrate characteristics of theoretical formula.

2. We can reproduce various situations by changing a parameter and can reproduce the situation that cannot be reality.

3. We can keep the cost low with only an initial investment.

4. By letting students create the teaching materials by themselves, students can understand theories of phenomena.

We show an example of application software to explain a principle of rainbow as an example of the teaching materials with computer simulation. Figure 9 shows an example of GUI screen of simulation program for explanation of rainbow.

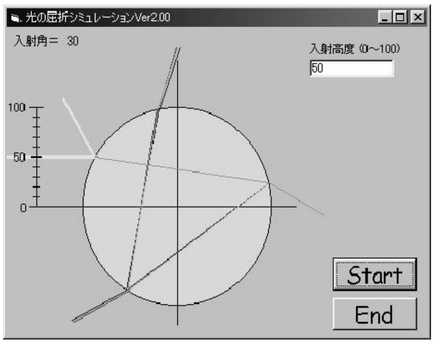

Figure 9. GUI screen of simulation for principle of rainbow. This program is created by a college student.

A teacher makes such a program and uses it for explanation of a principle. Sometimes we let students make program based on the principle after having let the students study the principle for himself. Through these works, we are developing teaching materials talking with the students. Thus the students deepen their understanding of the principle talking with us.

As other computer usages, we can use software for computer graphics (CG). We use CG software of POV-Ray[11] and reproduce atmospheric optics phenomena on a computer. It is useful for understanding of natural phenomena. POV-Ray is free software whose usage is simple and which can produce complicated pictures. Figure 10 shows an image of rainbow that we reproduce in defiance of influence of the ground. Actually it is difficult to observe such rainbow. However, with a computer, we can create it easily. There is some significance in education about using such teaching materials as CG.

Figure 10. Computer Graphics of rainbow.

5. SUMMARY

We demonstrated scattering phenomena seen in the atmosphere. These demonstrations are for students in junior high school, senior high school, and college. We let college students make programs in addition to experiments and simulations. This is training for thinking about a physical phenomenon from a teaching point of view through making the teaching materials. Some of these demonstrations are also suitable for a cultural lecture designed for the public. A basic way of thinking about these teaching materials exists in using a natural phenomenon around us as the teaching materials. There are a lot of teaching materials around us in addition to those which we used in our demonstration. Now people, especially young, are getting less interested in science. Against the background of this situation, it will become more and more important for us to encourage people to have scientific point of view and scientific way of thinking.

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