

Atmospheric Phenomena in Physics Teaching

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Abstract

According to International researches, physics teaching has difficulties all over the world. The majority of students do not like physics. It is an important object to find those topics that stir enough the curiosity of the students. In our opinion, some interesting topics chosen from the field of atmospheric physics could be an appropriate tool of that. More precisely atmospheric optics would be perhaps one of the possibly best choices. The topic used by us is the phenomenon of halos, which has certainly been proved to be an interesting subject for high school teenagers. Several tens of individual halo forms are known because the various shapes and orientations of tiny hexagonal ice prisms allow light to take numerous different paths in an encounter with a crystal, ranging from simple refraction paths through a wedge to complex ray paths with several internal reflections. In this article the physics of halos and the results of a project made by Hungarian students will be shown.

1. Motivation

The Earth's atmosphere and processes occurring in it are very interesting and our everyday life is highly influenced by them. Clouds, thunderstorms, lightning and rainbows are beautiful, sometimes frightening and exciting phenomena. There are numerous people fanatically observing, taking photos and videos of them almost on daily basis. In spite of that, mainly due to the complexity of the processes mentioned above, curriculums deal with this field of physics only very modestly. However, it is not difficult to excite the curiosity of the students by these admirable spectacles.

As it was mentioned, in the atmosphere very intricate processes can occur and at the same time a lot of measured data is easily accessible for all. Therefore meteorological data, satellite and radar images of the atmosphere provide wide possibility for teachers to set project work for students to do self sufficient research-work.

The atmospheric physics covers almost all the branches of the classical and modern physics, so it provides good possibility to find problems to illustrate the application of basic ideas and laws of various fields of physics. Without the demand of completeness we recite a list of field which is connected with atmospheric physics: atmospheric electricity, optical phenomena of the atmosphere (rainbows, halos, lightning, etc.), properties of the gases, fluid dynamics, weather forecast, atmospheric radiations, green house effect and so on. Most of these topics can be illustrated with beautiful pictures and videos available on the Internet, as well as with self made pictures, and the physical background of them can be treated at different levels depending on the previous experiences of the students.

However, the explanation of the observed phenomena may be quite involved, so the teacher should master the underlying subjects in order not only to identify and convey the most important messages, but also to provide correct answers to students' questions. In some cases the discussion of atmospheric phenomena is not recommended, to avoid difficulties and confusion which could discourage the audience. Furthermore, these phenomena can be treated at different levels. At introductory level a qualitative description with pictures and videos and spectacular simulations could be very impressive and meaningful. A deeper discussion can be easily built on this expressive material. This method fits well to the concept of a spiral curriculum in which there is a reiteration of concepts and subjects throughout the course. Each time the concept is repeated, more in-depth knowledge is presented so that each successive encounter of the concept builds on the previous one.

In an earlier work (Ságoti et al.) we gave a relatively broad picture about the branches of atmospheric physics which can be used in secondary school teaching for the motivation of students. [3] In the present paper we demonstrate this possibility with a little bit more detailed discussion of only a segment of atmospheric optics namely the ice halos.

2. Halo forming ice crystals

Notes about halos are known from the 16th century. Halos are sometimes strange, coloured arcs on the sky, mainly around the sun. Their origin is similar to that of the rainbows, but while rainbows are caused by the refraction of light on water droplets halos are the results of refraction on small ice crystals. Consequently, the most beautiful halos can occur in the Antarctic where the air is very cold and dry so ice crystals are growing quickly to form halos. Unlike water drops the form of ice crystals (and their orientation to the sun) can be very various and it diversifies the form of halos.

Halos can be seen all the year round from the tropics to the poles. They are produced by the ice crystals in cirrus clouds. The clouds are 5 to 10 km high and are always cold regardless of their location. In very cold weather halos are also formed by crystals in air close to ground level, also known as diamond dust.

Ice crystals behave like diamonds or other gem stones. As the sunlight passes between their faces it is refracted and reflected to send shafts of light in particular directions. Halos are in fact the collective glints of millions of crystals. The crystals are thin, hexagonal plates and six sided columns. Ice has hexagonal molecular symmetry (Fig.1) and as a consequence of this crystals are mostly hexagonal prisms that vary in proportion or habit from long columns to thin plates.

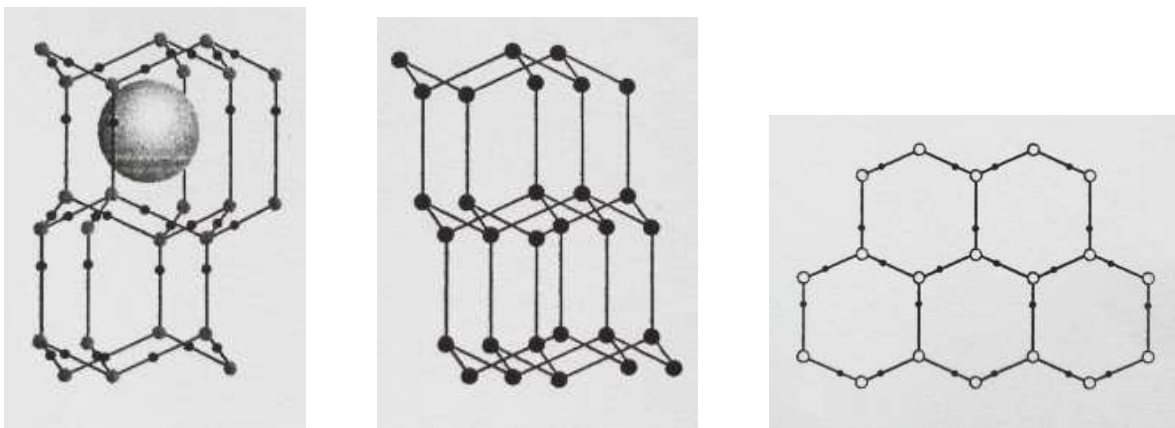


Figure 1. Ice has a hexagonal molecular symmetry [2]

Plate crystals have large faces, which are almost horizontal. Columns align themselves with their long axes nearly horizontal. Crystal habits, wedge angles and alignments are the keys to understanding halos. Snowflakes are large and complicated hexagonal symmetry crystals and in general they do not form halos with the rare exception of some occasional sun pillars.

2. Classification of halos

The observation of the haloes ensures the possibility for pupils to exercise some basic steps of the scientific research. It is very important the rigorous observation and the description of the phenomena investigated. Since the shape of the haloes can be very complex it is also very important the

classification of them. To observe and make a photo of a rare phenomenon is a real success for a keen halo hunter.

One way of classifying halos is based on the shape of halo forming crystals.

Columns	Plates	Pyramids
22° circular halo	Parhelia (sundogs)	9° circular halo
Upper tangent arc	Circumzenithal arc	18° circular halo
Lower tangent arc	Sun pillar	20° circular halo
46° circular halo	Circumhorizontal arc	23° circular halo
Supralateral arc	Parhelic circle	24° circular halo
Infralateral arc	46° parhelia	35° circular halo
Parry arc	Subsun	23° parhelia
	Lowitz arc	23° tangent arc
	120° parhelia	

Table 1. Classification of halos 1.

Another classification of halos may occur on the basis of the frequency of their appearance.

Type of halo	Relative frequency
22° circular halo	100
Parhelia (sundogs)	73
Tangent arcs	27
Sun pillar	16
Circumzenithal arc	13
Parhelic circle	4
46° circular halo	3.9
120° parhelia	1.2
Parry arc	1.1
Halos caused by pyramid crystals	0.3
Supra and infralateral arc	0.3
Subsun	0.2
Circumhorizontal arc	0.1
Others	1.5

Table 2. Classification of halos 2. (The column is result of German Halo Research Group) [3]

As for introducing the subject to high school students, the most effective way would be the observation of the phenomena, therefore the latter classification is more important for us.. However, sometimes it is a difficult task to recognize and classify the halos observed, therefore a short catalogue of them are presented in the following. Harald Edens’s descriptions were partially used to introduce the types of halos. [7]

4. Frequent ice halos

Fig. 2 shows a schematic picture of the frequent halos. They are the following:

22° circular halo is a halo around the sun or moon with a radius of 22 degrees, caused by refraction of light by randomly oriented hexagonal ice crystals. This halo is very common. Often, it is very faint,

but in some cases it will be brilliant and complete. The inner edge of the halo is reddish coloured, while the other colours of the spectrum are overlapping on the outer side of the halo, making it yellow to whitish.

The 22° left and right **Parhelia** (or **sundogs** / mock suns) of the sun are very frequent phenomena. Like the 22° halo, they are caused by refraction of light through hexagonal ice crystals, here in the shape of plates which float horizontally. Sometimes, they show very pure spectral colours, because as the crystals are oriented, there are very few skew rays through the ice crystal, interfering with the properly refracted rays, as in randomly oriented crystals. The latter produce elongated parhelia show less colour saturation.

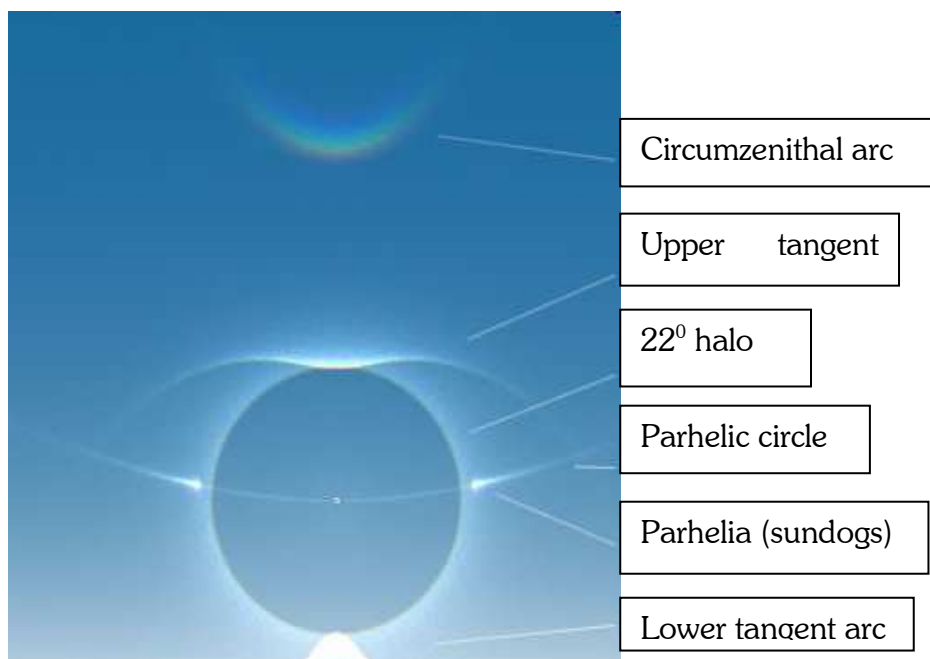


Figure 2. Frequent ice halos [4]

The **Circumscribed halo** is caused by sunlight being refracted by horizontally floating hexagonal ice crystal columns. The appearance of the circumscribed halo varies greatly with the height of the sun. If the sun is in the zenith, it is a complete circle. When the sun is lower, about 60 degrees high, it is shaped like an ellipsoid. Even lower sun elevations, the circumscribed halo becomes wider until the lower and upper half do not touch anymore. When it reaches the value of 10 to 20 degrees, the halo attains the shape of a V above the sun, referred to as the **Upper tangent arc** while the lower tangent arc is the V shape below the sun. The upper and the **Lower tangent arc** are part of the circumscribed halo.

Sun pillar can sometimes be seen above the sun when it is setting or rising. It is caused by reflection of light off the base of horizontally aligned plate ice crystals in the atmosphere. The extension of the pillar is usually only a few degrees very rarely it can be as much as 20 degrees or more. Light pillars are possible to be seen both above and below the sun or moon; however, for earth-bound observers, the upper light pillar is most common, while the lower pillar is more likely when you are in an airplane. The upper and lower light pillars at the sun can be present together with the parhelic circle and then form a giant cross in the sky, which was considered an omen by the ancient and medieval people.

The **Circumzenithal arc** is caused by sunlight being refracted by ice-crystal plates floating horizontally in the atmosphere. The light enters the top face of the plate and exits a side face. As the crystals have freedom of rotation along their vertical axis, an arc is produced with constant elevation, therefore a part of a circle with the zenith at its centre. Only the quarter circle towards the sun is visible. In rare cases,

the circle has a larger extend, and in extremely rare cases, it may be completed by an arc on its other side, being referred to as Kern's arc.

5. Infrequent ice halos

The picture of these haloes are summarized in Fig.3.

The **Parhelic circle** can be an impressive white arc spanning 360 degrees in azimuth. It is parallel to the horizon, and at the same elevation as the sun and it runs through the sun, the two 22° parhelia, the two 120° parhelia and the anthelion. (The **anthelion** is a spot on the parhelic circle opposit the sun.) The parhelic circle is caused by sunlight reflecting from the vertical faces of horizontally aligned, plate-like ice-crystals.

The **120° Parhelia** are caused by refraction and multiple reflections of light in horizontally oriented plate-shaped ice crystals. Unlike the 22° parhelia, the 120° parhelia can be visible with any sun elevation, not just low elevations. The 120° parhelia appear at the same elevation as the sun, 120° in azimuth on both sides of the sun. They are silvery white, colorless spots of light, and because of that, they will easily remain unnoticed.

The **46° halo** is a halo around the sun or moon with a radius of 46 degrees, caused by refraction of light by randomly oriented hexagonal ice crystals. This halo is rare, in extremely rare cases it may actually be seen as a complete circle. The 46-degree halo shows a much clearer color spectrum.

The most common are the upper sunvex and suncave **Parry arcs**, referring to their shape - convex or concave towards the sun. It is a variation of the standard upper tangent arc, and is also caused by horizontally oriented ice crystal columns, but these do not have a freedom of rotation along their long horizontal axis - one of the side crystal faces must be parallel to the horizon. The upper suncave Parry arc is like a second upper tangent arc, just over the normal tangent arc. Lower Parry arcs are also possible.

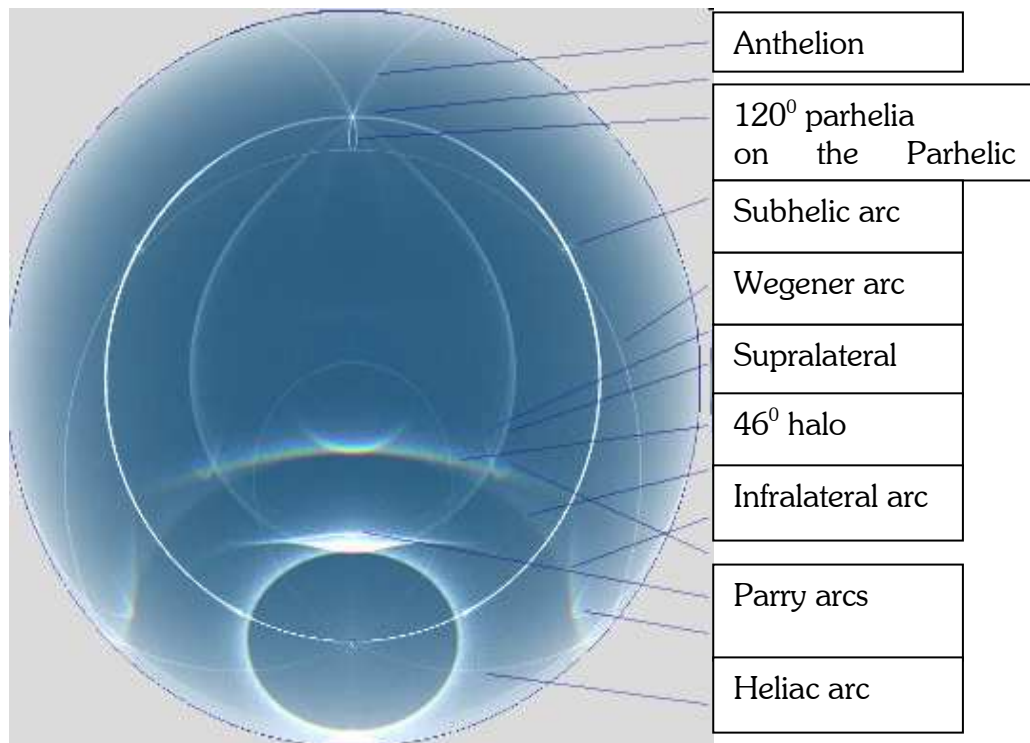


Figure 3. Infrequent ice halos [4]

The **Supralateral arc** is the 46-degree variant of the 22-degree upper tangent arc. It is caused by refraction of light by horizontally oriented hexagonal ice crystals columns. Light enters one of the side faces of the crystal column, and exits via a vertical end face. The supralateral arc is easily misinterpreted as being part of the 46-degree halo, as it follows about the same curvature. Other halos presence should be taken into consideration in order to define if it is a case of a superlateral arc. For example, when only circular halos are present, this is an indication that only randomly oriented ice crystals are present, and the 46-degree arc is actually a 46-degree halo.

Infralateral arcs are two arcs to the lower left and lower right of the sun, at a minimal distance of 46 degrees, and curved outward. They are produced by light being refracted through hexagonal, horizontally aligned ice crystals columns. Light enters one of the vertical end faces and exits a side face.

The **Circumhorizontal arc** is a beautiful, large, colored arc, which usually lies close to the horizon when visible. It is closely related to the circumzenith arc; it is caused by the same plate-ice crystals (and Parry-oriented hexagonal column crystals). Light enters one of the vertical side faces of the crystal and exits at the bottom face. The circumhorizontal arc can only be visible when the sun is higher than 58 degrees above the horizon.

Lowitz arcs are formed when plate ice crystals are spinning along their horizontal axes. As the spinning ice crystals have one more degree of freedom of rotation than those responsible for the parhelia, an arc is formed rather than a spot of light. Lowitz arcs extend from the 22-degree parhelia down to the 22-degree halo (the lower Lowitz arcs), and up between the circumscribed halo and the 22-degree halo (the upper Lowitz arcs). These arcs are very rare.

A **Subsun** is caused by horizontally-floating ice plate crystals. The millions of crystals reflect the sunlight. The more aligned the crystals are, the better the visibility of the subsun will be. The effect is relatively rare, only because the ice cloud has to be below the observer, like an airplane flight or from another elevated position.

Wegener arcs are an extensive set of arcs, touching the 22 degree upper tangent arc over the sun, curving past the zenith, and crossing each other and the parhelic circle in the anthelion. They are a very rare occurrence. The arcs are produced by light being refracted and internally reflected in horizontally oriented, hexagonal ice-crystal columns.

6. Examples for the theoretical explanation of the halo formation

Besides the observation it is also very important the interpretation of the observed phenomena and find out the crystal form caused the observed phenomenon. In the following a short theoretical explanation will be given for two frequent halos.

Dependence of Circumzenithal arc's radius on altitude of the sun

This arc is arising due to the refraction of the light on plate ice crystals. The sun rays enter to the top face of crystals and go out on their side face. These crystals are floating horizontally and can freely rotate around their vertical axle. Therefore the observer can see light rays coming from different direction. However, these light rays makes the same angle with the vertical line. It means that the observed arc must be a part of a circle around the zenith.

In this case the crystals refracting the light behave as a (Fig.4 and Fig5) right angle prism. Using the notation of Fig.5 the Snellius-Descartes law can be written for the refraction on the two faces of the prism, where ω is the direction of the sun and ε is the half of the vertex angle of the cone determining the Circumzenithal arc.

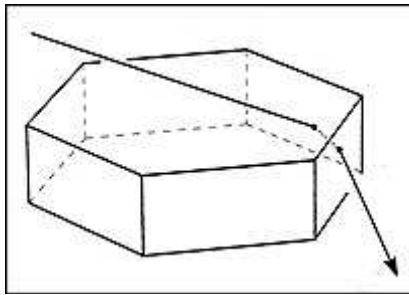


Figure 4.

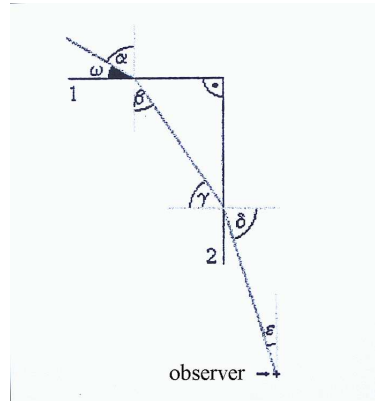


Figure 5.

$$\frac{\sin \alpha}{\sin \beta} = n$$

$$\frac{\sin \delta}{\sin \gamma} = n$$

Since

$$\alpha = 90^\circ - \omega$$

and

$$\delta = 90^\circ - \varepsilon$$

$$\frac{\sin(90^\circ - \omega)}{\sin \beta} = \frac{\cos \omega}{\sin \beta} = n$$

and

$$\frac{\sin(90^\circ - \varepsilon)}{\sin(90^\circ - \beta)} = \frac{\cos \varepsilon}{\cos \beta} = n.$$

From these equations:

$$\frac{\cos^2 \omega}{n^2} = \sin^2 \beta$$

and

$$\frac{\cos^2 \varepsilon}{n^2} = \cos^2 \beta,$$

so the vertex angle depends on then elevation angle of the Sun according to the equation:

$$\cos \varepsilon = \sqrt{1 - \cos^2 \omega}$$

Sometimes these arcs are very impressive due to their rainbow like brilliance and saturation of the spectral colours. The spectral colours are much more vivid than those either of the refraction haloes.

Dependence of Circumhorizontal arc's radius on altitude of the sun

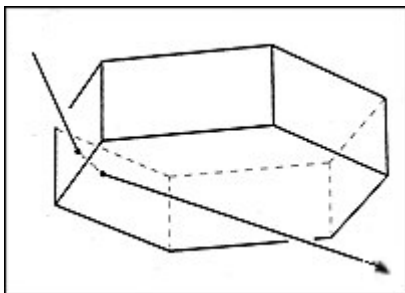


Figure 6.

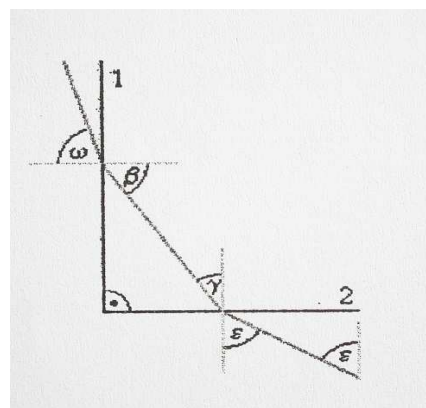


Figure 7.

This arc comes into existence due to the sun rays enter to the side face of crystals and go out on their base. Then the crystals behave also as a (Fig. 6 and Fig. 7) right angle prism. Using the notation of Fig. 7 we can do an analogous calculation to the former one was applied for the determination of the angle of the Circumzenithal arc.

The result is that the half of the vertex angle of the Circumhorizontal arc depends on the elevation angle of the sun:

$$\cos \varepsilon = \sqrt{1 - \cos^2 \omega}$$

7. Simulation of halos

The most important properties of the haloes can be interpreted on the basis of the laws of geometrical optics. Mathematically this is not an intricate task therefore to make programs which simulate haloes is a solvable task. (Although to take into account the great variety of the crystal forms is not too simple.) From the internet we can download freely an excellent program for this.

HaloSim3.6 created by Les Cowley, Michael Schroeder is a software for simulating halos. The program calculates the different light paths arising due to the refraction of light on various crystals and display the corresponding haloes on the celestial sphere. HaloSim uses exact mathematical descriptions of cloud ice crystals. A crystal is defined by specifying all its faces. When starting a simulation, HaloSim reads the constants defining the planes passing through the faces and their normal vectors from individual crystal shape files. These data together define limits for the range of angles the crystal can make to the sun and horizon. Then the simulation starts. The number of rays that reach a pixel determines the local halo brightness. The ray tracing is repeated for up to several million rays to produce the simulation. To find out the crystal form which produce an observed halo phenomena is very exciting task for students. During this they got lots of knowledge about ray tracing and the properties of crystals.

8. Results of project: our halo photos and their simulations

In February 2009 spectacular atmospheric optical phenomenon were visible in Hungary. Then one enthusiastic group of students decided to make observation concentrating on atmospheric optical phenomena.

The aim of the project was the familiarization with the halo phenomena with a view to its theoretical and practical aspects. They wanted to reveal the origin of halos, types of the halo forming ice crystals, possibilities of orientations in space, types of phenomena and their simulations .

The ordinary person of our accelerated world today has alienated from nature, it is not obvious for them to pay attention to nature. Therefore, further aim was to make independent observations and document it with photographs. They have been introduced to OPOD (Optics Picture of the Day) website, where the world's most beautiful atmospheric optics pictures can be seen.

At the beginning we formed an information chain. When someone (at first usually the project supervising teacher) observed a phenomenon, with the help of the chain everybody got to know about it, so they knew that they had to look up on the sky and take photographs. Later they were able to observe and study the phenomena on their own, without using the information chain.

Simple forms of halos can be observed relatively often. However, taking photos of them can be a challenge because the photos should be taken against the sun and should use a special lens. Most compact digital cameras have only a 35 mm focal length lens. They are not the most appropriate tools for photographing halos as it can capture only a fraction of the sky. If we attempt to take a photo for example of a 22-degree halo (it measures approximately 44 degrees x 44 degrees), we will notice that

only a little more than a half of it will fit in the frame as the visual angle of a 35 mm-focal-length camera in only 55 degrees x 36 degrees.

Therefore it is advisable to use a camera with bigger visual angle but with no more than 28 mm focal length lens (66 degrees x 44 degrees). It would enable us to document halo phenomena more effectively. The best possible instrument to photograph halos is the so called “all sky camera” or “fisheye lens”, which has a visual angle of about 150-180 degrees.

It is very important to cover the sun and its immediate surroundings while taking pictures, because the camera can get damaged by the strong sunlight. Nearby objects in our surroundings can be useful to cover the sun but we can also create our own “suncover”, specially designed to photograph halo phenomena. In spite of this there are halo “hunters” all over the world and students are often very keen on photographing these phenomena. Moreover the observation and documentation of the halos can be combined with enjoyable simulations of the previously mentioned halosim program available on the Internet.

After recording the phenomenon we tried to induce it by simulation. The parallel pictures – some of the simulation pairs can be seen below (Fig.11).



Figure 8. Halo performance by students of Garay Grammar School, Hungary



Figure 9. 22-degree halo

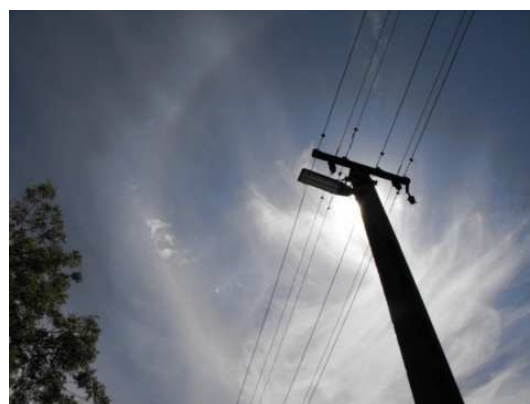
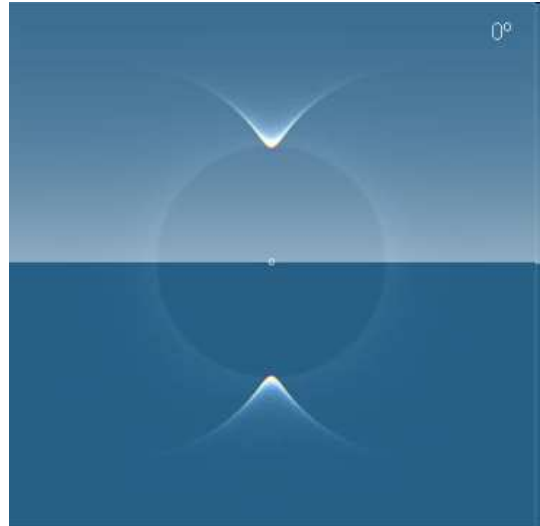


Figure 10. 22-degree halo



**Figure 11. Upper tangent arc and its simulation (the height of the Sun is about 0°)
The figure on the left is a photograph while the one on the right is a simulation.**

9. Conclusions

To strengthen the students' internal motivation for learning physics is a basic goal of teachers. Present paper suggests a collection of phenomena taken from the field of atmospheric physics to help to achieve this goal. These phenomena can be entered into the curriculum in very different ways. They might be illustrations of the basic laws of physics, but some topic of it could serve as a project work.

Acknowledgement

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