Simple experiments with the rainbow

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We describe miscellaneous experiments on rainbow formation and its properties.

Introduction

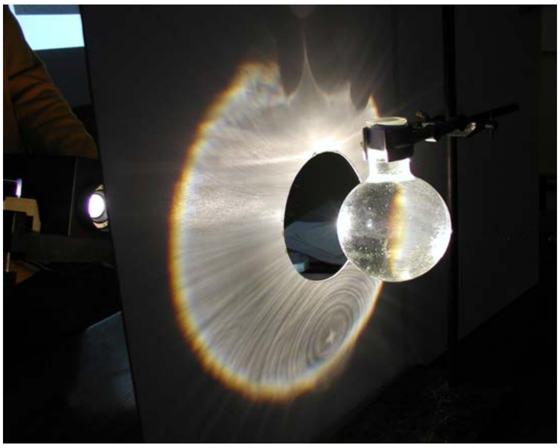
In December 2014 a large installation at Amsterdam Central train station was opened. This artwork is in the form of a rainbow that is projected on a large arch construction that spans over the platforms. A curved spectrum that follows the shape of the roof is created with the use of a not so simple technological device: a patterned liquid crystal polarization grating. Throughout 2015, the International Year of Light, the rainbow will appear for a few minutes every evening after sunset. The precise time of its appearance is a surprise, just like with a real rainbow.

As we have a keen interest in atmospheric optics, the project in Amsterdam has led us to the idea of describing a whole series of experiments prepared in the last several years to illustrate rainbow formation and its properties. These experiments are quite simple as the general setup consists of an appropriate light source, a raindrop (or its model or a counterpart) and an observation screen located in a properly chosen place. Of course, a well darkened room is a must.

Main experiment

Our favorite experiment is that in which a drop is simulated by a round flask (spherical container with a narrow neck) filled with water. The first experiments of this kind were performed in the Middle Ages. After studying such a magnified drop model, Theodoric of Freiburg showed that light must both refract at the surface and reflect on the inside of each individual drop of water rather than from the entire cloud.

We recommend the version described in the classic book of Minnaert [1]: a screen with a round aperture that is a little larger than the flask is placed between the flask and a bright source of near-parallel light. The Sun itself would be ideal as a light source but is usually not available in a classroom so a slide projector is applied. The backscattered light forms a circular rainbow on the screen. The reds and oranges are apparent but the blues and greens are not so. In order to get better colours one should use a carbon arc lamp with condensing optics.



This experiment is an excellent material for observation. By blocking small parts of the incident light one can discover, as Descartes did, that the rainbow is formed only by certain rays. If one holds a ring a few millimeters thick and in diameter 0,86 times the diameter of the flask carefully centered in the incident beam, the rainbow will disappear altogether. The first satisfactory explanation for the rainbow was achieved by Descartes after additional lengthy calculations of the light ray paths in the spherical raindrop: the geometry and the laws of ray optics place the red part of the primary rainbow at about 42°, measured from the initial direction of the rays. It is in agreement with a fact noticed as early as the 13th century: the rainbow is always seen in the direction of 42 degrees from the anti-solar point and at a specific and narrow range of angles close to it. The crucial point in Descartes' explanation is the following: the rainbow happens at the angle of the densest clustering of the rays leaving the drop (so it is a caustic effect), which coincides with the angle of the least deviation (the so called Cartesian rainbow angle).

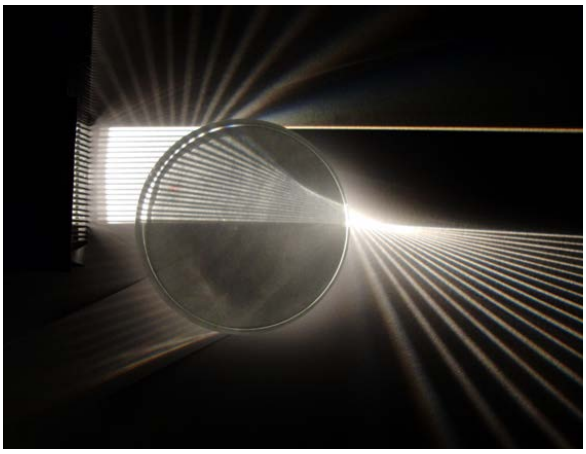
When the screen is moved slightly away from the flask, the secondary bow appears around the aperture. It has exactly the same explanation as the primary one, except that the rays causing it undergo two internal reflections.

There is a noticeable intensity difference between both sides of a colour bow. This is responsible for an interesting property of the primary rainbow: the sky is brighter inside the rainbow than outside. The reason for this is that light cannot be scattered by rain drops by less than the minimum angle of deviation. When combined with a similar effect for the secondary bow, it gives rise to Alexander's dark band in nature.

After placing a polarizing filter between the globe and the screen one can easily verify that the light of the rainbow is nearly completely polarized.

Nonuniformity of glass walls substantially influences the display (darker and brighter bands easily seen in the photo). The lack of ideal sphericity causes distortions of the bow. A glass or a plastic acrylic transparent sphere may be substituted for the flask of water giving a really smooth picture with an ideally circular bow but in this case the secondary bow is not seen.

Two-dimensional version



For smaller groups of students, the two-dimensional version of the experiment is more appropriate: a parallel beam of white light from a light box illuminates one half of a plastic transparent disc. The above mentioned properties are also easily demonstrated in this case. Furthermore, when the beam is divided into many rays (for example by a comb) it is possible to trace the path of every single ray. In this way one can check experimentally that for a drop model there is no total internal reflection. This is important in teaching on the rainbow as in many printed Polish sources (textbooks, encyclopedias) it is explicitly stated that rainbow formation is accompanied by the total internal reflection of light.

Among the rays leaving the disc after the second refraction one can find two which follow almost the same path near the rainbow angle direction. This supports the evidence of ray clustering.

The angular radius of the bow here is only about 21°, half of that of a rainwater bow because acrylic plastic is more strongly refractive. In order to measure the value of the genuine rainbow angle it is enough to pass light through an inverted plastic cup with straight walls partially filled with water (by the way, it is much easier available than a plastic disc).

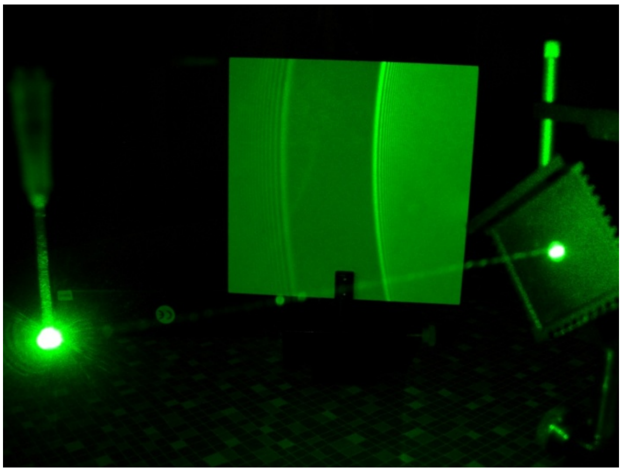
Rainbow from glass beads

Sometimes one can observe the rainbow effect on recently painted asphalt. The bow is produced by tiny glass spheres (their diameters are usually in the range from 0,1 mm to 0,3 mm) sprinkled onto the road to enhance the reflectivity of paint markings. In order to make an indoor glass beads bow display one needs to attach a layer of beads to black cardboard using adhesive in aerosol spray can. Then it should be illuminated by very bright and small light source. We got the best results using a bulb with the so called point-like filament. The glass beads can be obtained from a local road repair department or ordered direct from manufacturers.

Higher-order rainbows

In 2011 tertiary and quaternary rainbows were first registered by making photos and subsequently applying extra image processing. While the 1st and 2nd orders are opposite the sun, the 3rd and 4th orders circle the sun. Although a combined contribution of rainbows with the number of internal reflections $n > 2$ together comprise less than 0,5 % of scattered energy, high order bows are quite easily produced under laboratory conditions with white illumination of a single water drop or a falling stable water jet. The rays forming each rainbow's rim (the minimum deviation or caustic rays) get closer and closer to the drop's edge. In our experiments we used a glass cup of cylindrical shape with thin walls as a model of water drop and a bright halogen bulb of 250 W with condensing optics as a light source. The essential thing here is that, beside reducing background light as much as possible, one must partially block the incident light for smaller impact parameters which give rise to smaller-order rainbows. For example, to get 3rd and 4th order bows we set the width of the slit in such so as a way to eliminate the first two colour bows. Naturally, very careful adjustment is required throughout this experiment.

Airy fringes



The last experiment reported here is crucial for explaining rainbow formation in a wave approach. When a drop (which is not of spherical shape but has circular horizontal cross sections), suspended from a needle of a syringe, is illuminated with a single colour (for example with the light of a laser diode) on a screen placed aside in the back direction, we can observe two spectacular interference patterns in the vicinity of Cartesian rainbow angles: a long series of fringes. They are usually called Airy fringes to commemorate an outstanding contribution of George Bidell Airy, then Royal Astronomer, who developed a mathematical description of intensity of light near a caustic in terms of certain definite integral. The interference occurs here between two arms of a cusped outgoing wave front.

Supernumeraries and fogbow

Because of dispersion the principal maxima for different wavelengths occur at slightly different angles. What is normally seen in the rainbows is the summation of these interference patterns for all the colours in the solar spectrum. When the droplet size distribution in a cloud is narrow inside an appropriate range, the result of interference is visible in the form of the so called supernumerary arcs (coloured fringes sometimes seen close inside the primary rainbow).

As the drop radius decreases, the maxima shift and become widen, so they overlap more and the colours become less saturated. Such change eventually destroys the distinguishability of colours. For very small drops (smaller than about 50 μm in diameters) what one sees then in nature is the so called fogbow or white rainbow, a phenomenon observed very rarely.

Both forms of the rainbow are not very frequent but an interested reader will find many spectacular photos of them (as well as of many other optical phenomena in the atmosphere) in the “Optics Picture of the Day”, which is part of one of the best web pages devoted to atmospheric optics [2].

References

[1] Minnaert M.: *The Nature of Light and Colour in the Open Air*. Dover, New York 1954

[2] www.atoptics.co.uk