Halo and mirage demonstrations in atmospheric optics

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Some laboratory demonstrations on atmospheric optics are presented. The focus is on dispersion effects in mirages, lateral mirages, and inferior mirages produced with small hot plates. We also show a demonstration of the upper-tangent-arc halo, produced with a hexagonal prism, rotating about two axes.

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1. Introduction

Laboratory experiments and demonstrations obviously complement observations and theoretical approaches in meteorological optics. Recently an extensive summary of demonstrations of rainbows, halos, and mirages was given.[1] The present paper discusses some additional demonstrations of halos and mirages.

2. Mirage Experiments

A. Superior Mirages: Dispersion Effects

An easy experimental demonstration of superior mirages consists of preparing a layer of fresh water above a saturated saltwater solution in a water tank and observing objects through the water tank.[1–3] Alternatively, systems of sugar solutions work well,[4] and also a temperature gradient, produced in the surface layer of water by infrared lamps above the surface, proved successful.[5] With these methods it is possible to demonstrate vertical stretching or compression as well as multiple-image mirages. In addition, the influence of turbulence can be studied.

With the same setup it is also possible to observe colorful effects from black-and-white objects. The object consists of the words *Fata Morgana*, printed in black on a piece of white cardboard with two colored tops at the sides. Observing this object through the water tank, which simulates an artificial inversion layer in the atmosphere, leads to the result of Fig. 1.

First, the superior mirage of the object is seen as a triple image. The angular size and separation of the three images depends on the observation angle and the orientation of the object with respect to the height of the artificial inversion layer between object and observer. Triple images are formed according to the scheme of Fig. 2 (compare also the discussion in Ref. 6). The effect of a temperature inversion in the atmosphere is replaced with a gradient of index of refraction between the two values of fresh water and saltwater [Fig. 2(a)]. Light rays at different heights in the tank will travel with curvatures illustrated by the rays in Fig. 2(b), following the general rule that light rays bend toward the direction of increasing index of refraction. Figure 2(c) shows the paths of some light rays from an object (the letter F) reaching an observer's eye through the water tank with an index of refraction according to Fig. 2(a). Rays 1–5 come to the observer from progressively larger angles. On the right-hand side of Fig. 2(c), the numbers show the part of the triple image mirage that corresponds to the depicted light rays.

Second, one can clearly see the colored fringes on the black-and-white words in the two top superior mirages in Fig. 1. Obviously, these colored fringes are due to dispersion effects within the artificial inversion layer. They can be seen best for objects with strong black-and-white contrast, and they are less prominent for colored objects such as the tops. Still, it seems possible that they might also show up in natural observations, the main problem being the exact knowledge of the color of the objects, which usually are kilometers from the observer.

B. Lateral Mirages

There have been many observations of lateral mirages, and it is said that Kircher successfully

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0003-6935/03/030394-05$15.00/0

(a)

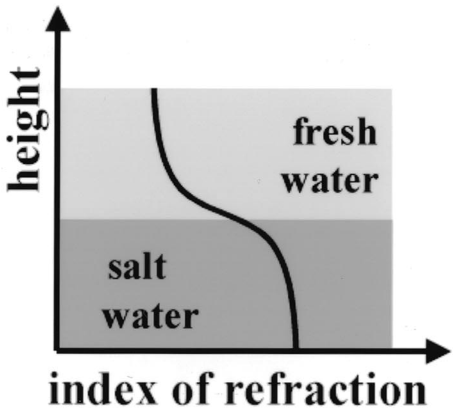
(b)

Fig. 1. Dispersion effects seen in a superior-mirage, saltwater-tank experiment. In both three-part mirages shown here, dispersion effects are clearly visible.

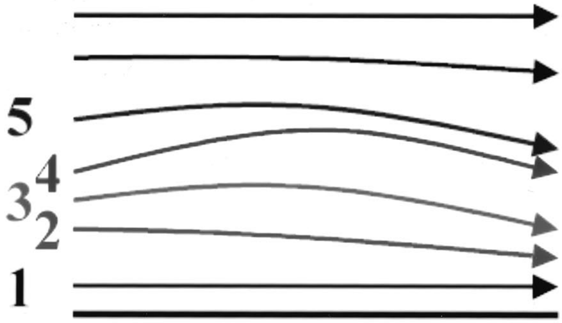
showed a demonstration experiment for some Roman cardinals.[7,8] He is said to have used a channel in the form of the street of Messina made of soil, sand, and rocks and heated the whole arrangement from below. Observing two fighting soldiers through this channel gave the impression of two fighting armies.

Since lateral mirages are nicely observable in nature, for example, as mirages from heated walls,[9] it seems reasonable that such a demonstration should be possible. Each soldier could be seen with mirror images from both sides of the channel. An experiment along these lines can be realized in the laboratory, by use of a U-shaped, flame-heated channel. This setup is similar to the one of the inferior mirages with heated plates,[1–3,10] the only difference being the geometry of the plate. Figure 3 depicts a photo of a toy figure of 3.5-cm height as observed through the U-shaped channel of width 3 cm, height 7.5 cm, and length 2.5 m. In this case one observes three images of the object. Observations with the naked eye are easier because the necessary long exposure times for the photo lead to blurry images. In the experiments, perception of more than three images can be regarded at least as being very difficult. However, observers not used to mirage images might interpret the blurring and lateral stretching as multiple images. In the context of the above description of Kircher's experiment, it therefore seems at least doubtful that, from two fighting soldiers, more than six soldiers should have been observable, which would seem to be less than two armies.

Lateral images may also be simulated experimentally by use of a simple plate oriented vertically, if it is heated electrically.



(a)



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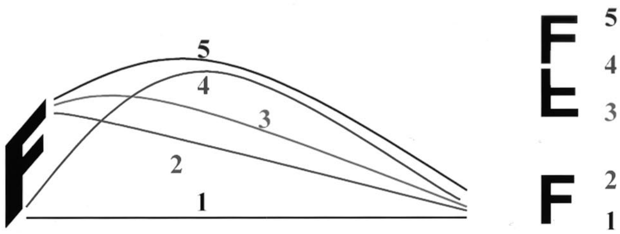
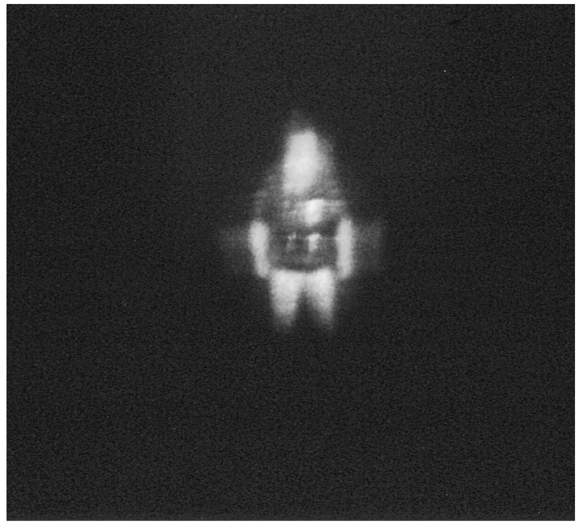


(c)

Fig. 2. Explanation of a three-part superior mirage in the water-tank experiment. (a) Index of refraction as a function of height in the water tank, (b) curvature of light rays traveling in the tank, and (c) formation of a triple image in such a demonstration.



(a)

(b)

Fig. 3. Lateral mirage: multiple images of a toy figure as seen through a U-shaped heated channel just before (a) and after (b) the mirage becomes observable.

C. Inferior Mirages with Small Hot Plates: Blowing Away the Light

Inferior mirage experiments are usually done with heated plates whose lengths are, e.g., 2 m or more.[1–3] However, such lengths are not necessary; it is possible to observe mirages with hot plates as small as 14 cm in diameter. These hot plates are also ideally suited to demonstrate what we might call the deflection of light beams by human breath.[11] The experimental setup (Fig. 4) consists of a hot plate and a laser that is adjusted at grazing incidence such that some of its light is scattered by the surface. In addition, one also observes the position of the light beam on a distant wall. Blowing onto the hot plate results in the upward deflection of the beam spot on the wall while, simultaneously, the scattered light on the surface of the plate is no longer visible. Figure 4 depicts the principle of the experiment with and without blowing. The real experiment is much more impressive than any photo of the effect.

The explanation for this phenomenon is as follows: By blowing, we remove the usually turbulent warm air above the plate. The colder air from the breath directly above the plate is heated up quickly and results in a much more homogeneous thin layer of hot air, which deflects the light beam using a much shorter heated surface than usual in inferior mirage demonstrations. It is also possible to observe inferior mirages from small objects (we used letters of size 5–7 mm) with such a setup. Using a fan for moving the air, one may turn the air flow on and off while simultaneously seeing the inferior mirage come and go.

This demonstration also works the other way around. A laser is adjusted adjacent to and paral-

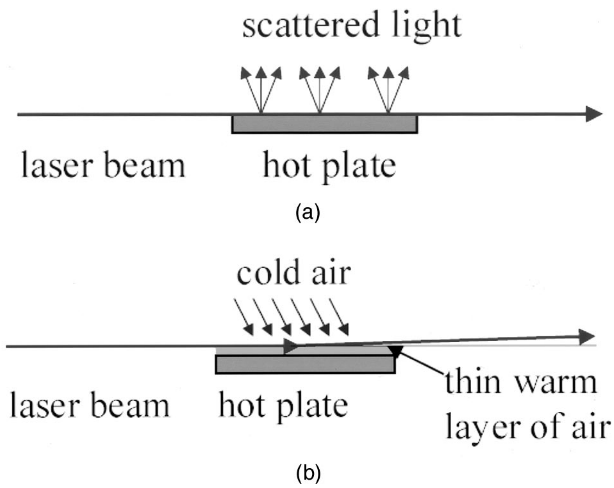


Fig. 4. Principle of a demonstration of blowing light away. In (a) laser light scattered on the hot plate is seen. When we blow colder air toward the hot plate, the light ray is bent away (b).

lel to a cold plate such that no scattered light from the plate is observable. Blowing with a hot fan onto the plate "blows" the laser onto the plate, resulting in stray light from the plate. Again a thin layer of air is formed, which is quickly cooled by the metal surface. The corresponding gradient of the index of refraction bends the light beam toward the plate.

3. Experimental Demonstration of Tangent Arc Halos

Several features of halos such as sun dogs, the parhelic circle, the circumhorizontal, the circumzenithal, and the Parry arc,[1,6] may be demonstrated by rotating prisms. We can simulate all these effects by sending light through a hexagonal prism rotated about one axis. For the first four effects the rotation is about the symmetry axis, which is constrained to be vertical. We rotate the prism, not because the crystals in the sky are rotating but because we are quickly giving our one prism all the orientations possessed by the many crystals in the sky. This corresponds to the orientations of a group of falling plate crystals. The Parry arc results from column crystals that fall with their axes horizontal and one pair of side faces also horizontal. All these orientations are given our one prism by means of spinning it about a vertical axis when its symmetry axis is horizontal and a pair of side faces are horizontal.

The method of orienting our single crystal to produce the upper tangent arc is more complicated. The collection of crystals to produce this effect is subject only to the restriction that the crystals' symmetry axes are horizontal.[6,12] For quickly giving our one prism all the orientations of this collection, we must keep the symmetry axis horizontal, spin the crystal about this axis, and simultaneously spin it about a vertical axis.

An experimental arrangement (see Fig. 5) was developed that allows simultaneous rotation around these two perpendicular axes. The hexagonal prism

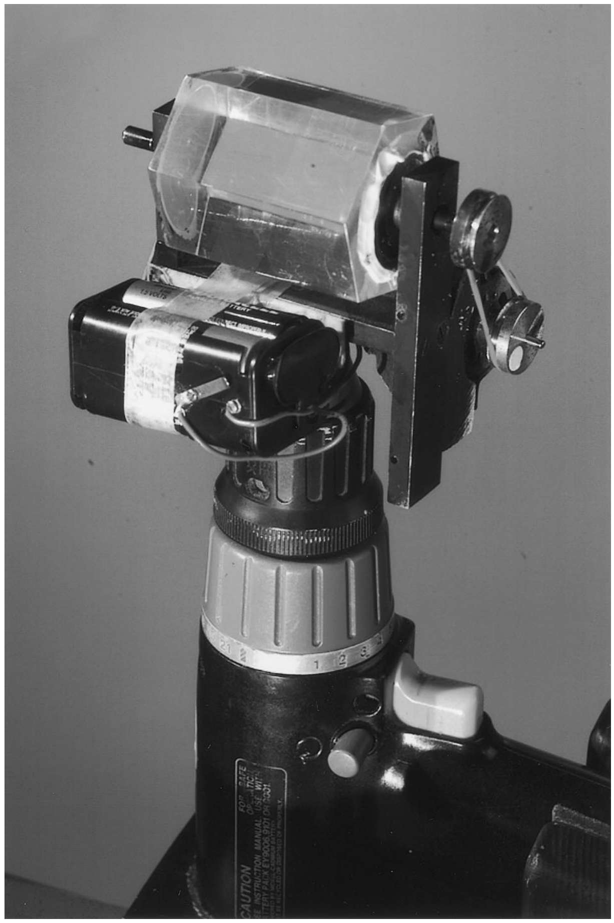
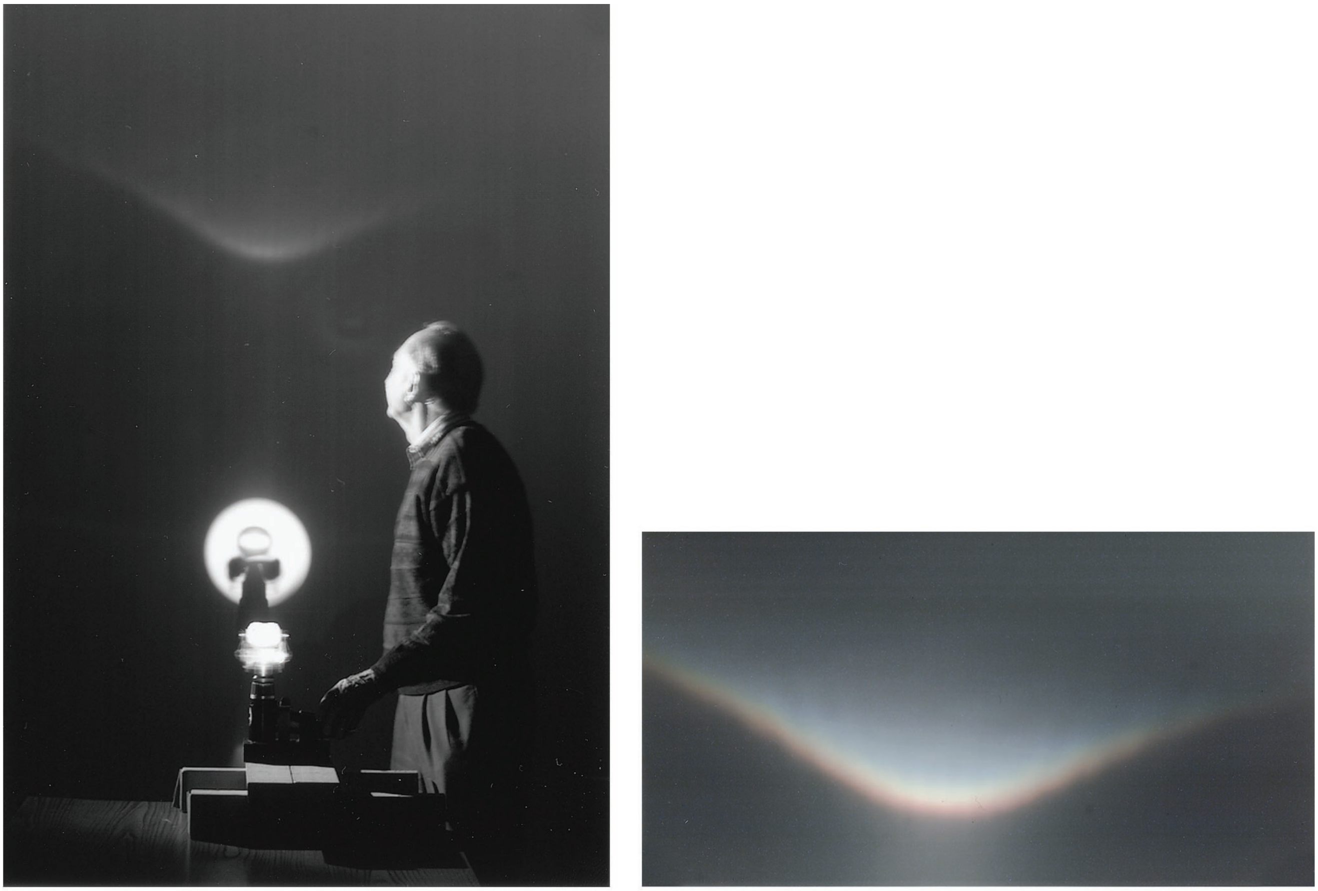


Fig. 5. Experimental arrangement for simultaneous rotation of hexagonal column crystals around two perpendicular axes.

is rotated about its horizontal symmetry axis by a small, battery-powered electric motor. This assembly is attached to a battery-powered drill. By operating both rotations and illuminating the device with light from a slide or overhead projector, we can experimentally simulate the tangent arcs on a nearby screen.[13] The experimental halo angles depend on the index of refraction of the prism. One may use, for example, either a sample made of glass or Lucite (polymethyl methacrylate) ($n \approx 1.5$) or a hollow body filled with water ($n = 1.33$) giving results closer to those of ice ($n = 1.31$). The shape of the upper tangent arc depends on the solar elevation, and we can show this effect by varying the angle with which the light approaches the rotating crystal. For example, with a water-filled prism, to simulate the upper tangent arc with the Sun at 30 deg above the horizon, the projector beam must come up to the crystal from a position 30 deg below the horizontal. To get a smooth, continuous pattern on the screen, the rotation about the horizontal axis must be fast enough—not less than ~4000 revolutions/min. Figure 6 shows an experimental upper tangent arc halo pattern, which nicely corresponds to the one expected for this kind of crystal ensemble, for a solar elevation of ~10 deg.



(a) (b)

Fig. 6. Experimentally simulated upper tangent arc resulting from light passing through a plastic hexagonal prism rotating about two axes: (a) setup and (b) close-up view of the arc.

4. Outlook

Demonstrations of natural phenomena, in particular those of meteorological optics, help students understand the physics behind these phenomena. They also motivate young students to take a closer look at nature and its many secrets. To make this experience available to many children and adults, we plan to include simple experiments on atmospheric optics in the permanent exhibitions of science centers and museums. As a start the Swiss science center Technorama in Winterthur will include experiments on the inferior mirage with a heated plate, the blowing away of light, and the superior mirages with salt solutions in an exhibition starting April 2002.

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