Rainbow-Like Spectra with a CD: An Active-Learning Exercise

G. Planinšič, University of Ljubljana, Ljubljana, Slovenia
A. Corona and J. Slisko, Benemérita Universidad Autónoma de Puebla, Puebla, México

Rainbow-like spectra, produced by reflexive diffraction of white light on a CD, offer a spectacular visual effect as well as an excellent classroom opportunity for students to learn how physics works. In this paper we show that building a coherent qualitative explanation can be a challenging task that requires students to combine gained knowledge with observations and explorations.

In a recent article in this journal,[1] Ouseph provided detailed instructions on how to use a CD to demonstrate spectacular reflection and transmission, and rainbow-like spectra to a large lecture hall of 200–300 students. He also described how to create interesting noncircular spectra by changing the angle of incidence of the light. Ouseph's results are a good starting point for designing some classroom tasks to involve students in active physics learning.

In this paper, we describe:

1. an active-learning sequence to engage students in simple explorations of circular rainbow-like spectra; and
2. a qualitative explanation of surprising results of those explorations.

Comparing Rainbows and Rainbow-Like Spectra

A good starter to engage students in this activity is to show them a photo of a naturally created rainbow and ask them to carefully compare its colors with those seen in the rainbow-like spectrum obtained when a beam of white light is reflected from a CD [Fig. 1(a)]. No doubt, students will rapidly discover that the two sets of colors, although at first sight quite similar, are not identical. For example, the rainbow-like spectrum created by reflection from a CD contains magenta, a color that is normally not observed in natural rainbows.

Fig. 1. (a) Rainbow-like spectrum caused by light reflection from a CD. (b) Spectrum obtained when the right-hand side of the CD is blocked with an opaque card. (c) Spectrum obtained when the left-hand side of the CD is blocked with an opaque card.

DOI: 10.1119/1.2971214

Knowing that magenta indicates a mixing of red and blue, its presence is the first useful hint for creating a physical model for explaining the observed properties of rainbow-like spectra. Such a model must provide the possibility that red and blue light, after diffraction off the CD, meet at points on the screen.

Effect on the Spectrum of Covering Half the CD

More informative hints for understanding a phenomenon are usually obtained when students not only observe but also explore the consequences of making some simple, specific changes. The exploration is more effective if students are asked, before a specific change is made, to predict what will happen and justify their prediction. This active-learning sequence is known as Predict-Observe-Explain.[2] The “Explain” part is normally needed in all well-designed sequences in which observations don’t fit predictions.

It is widely known[3] that most high school students (and even many university students), when asked to predict the effect of covering half of the lens producing an image on a screen, would claim that half of the image would disappear. We have found it useful to apply this idea of modifying a lens to the situation in which a rainbow-like spectrum is created by a CD.

So, the next step in the active-learning sequence is to ask students to predict what should happen to the spectrum on the screen if half of the CD is covered. It is very likely that many students will say that half of the spectrum should be missing.[4] Nevertheless, the observed patterns with the right or left half of the disk covered only partially fit that prediction [Figs. 1 (b) and (c)]. That is, when the right half of the CD is covered, the right part of the outer circular spectrum indeed disappears. But the right half of the inner circle still appears on the screen. What is missing is the left part of the inner circle [Fig. 1(b)]! And when the left half of the CD is covered, the right part of the inner and the left half of the outer circular spectrum disappear, but the left part of the inner circle is still seen on the screen [Fig. 1(c)]. So the behavior of the outer circle, after one half of the CD is covered, fits the prediction based on an intuitive model, and the behavior of the inner circle challenges this model.

In addition, those students having eagle-like eyes will detect another surprising detail: magenta is now missing! After students have been surprised by these counter-intuitive effects, they should be motivated either to try to construct their own explanation of the surprising facts they learned or to listen carefully to how their teacher would explain them. In what follows, we offer a possible way of constructing such an explanation.

Constructing a Qualitative Explanation

The tasks of providing a qualitative explanation of 1) the appearance and disappearance of the magenta band and 2) the different behavior of the inner and outer circular spectra observed when half of the CD is covered require deeper understanding of how a CD “rainbow” is formed.

This is a multi-step problem solution that calls for a synthesis of different representations and offers several opportunities for experimental verification. It can be used also as an example of an expert-like approach to solving complex qualitative (and quantitative) problems in physics. A well-known tactic is to start with a simplified version of the problem (in this case, understanding the behavior of monochromatic light before trying to deal with white light).

The key steps in building the explanation of the observed facts about rainbow-like spectra are:

1. Understand that the CD works as a reflective diffraction grating.
2. Understand how the diffraction pattern is formed when a simple light source—the narrow monochromatic coherent light beam from a laser—is incident perpendicularly on the CD and how this pattern depends on the wavelength (color) of the light.
3. Understand that if the laser beam is made wider (for instance, by using a beam expander), the beams of diffraction maxima will also become wider (many students think that diffraction pattern is “focused” on the screen as a result of converging rays).
4. Understand the formation of the diffraction pattern obtained when a wide beam of monochromatic light (with diameter equal to or larger than the diameter of the CD) is incident perpendicularly on a CD. First, the formation of the diffraction

pattern in a plane passing through its center should be explained (two-dimensional analysis). Then the complete diffraction pattern can be thought of as a rotation of the two-dimensional solution about the symmetry axis of the CD.

5. Explanation of the formation of the pattern obtained when white light is used and half of the CD is covered, including the explanation of the CD rainbow and the appearance of the magenta color. This may come as a result of the Predict-Observe-Explain sequence[4] based on the steps taken above.

Since steps 1 to 3 are generally known and well-documented,[1-4] we will focus here only on steps 4 and 5.

As one can easily demonstrate, the diffraction pattern obtained using a green laser as the light source shows a central reflected beam and two diffraction maxima on each side of it. A red laser can also be used, but since the eye's sensitivity is higher for the green light, the green laser is superior for these demonstration experiments. Simple measurements show that for the green laser, the first-order maximum appears approximately at an angle of about 20°.

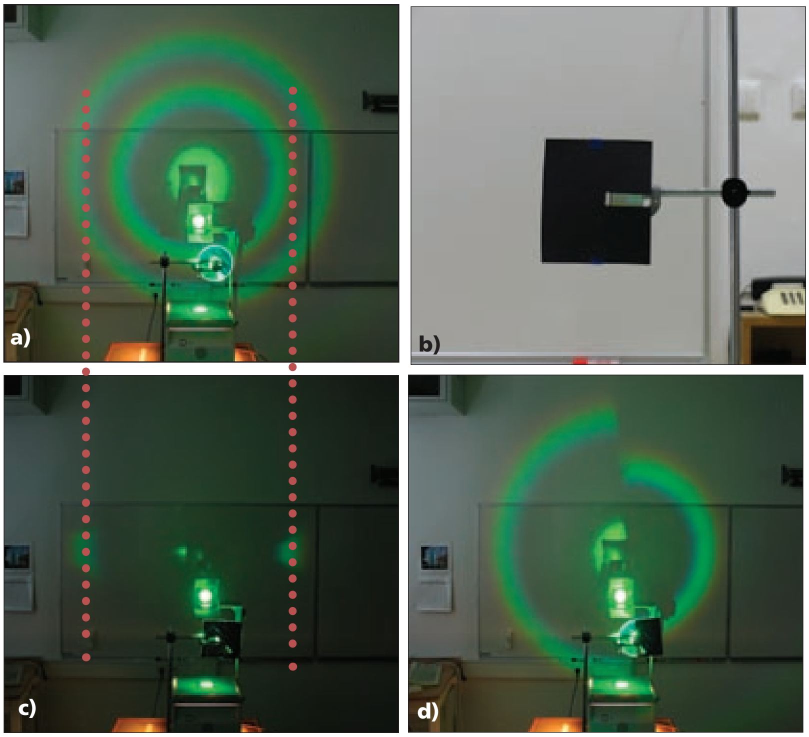

Fig. 2. (a) Diffraction pattern when the CD is uniformly illuminated with green light. (b) Black paper mask covering all but a radial strip of the CD. (c) Diffraction pattern with the mask in place. (d) Diffraction pattern when the right half of the CD is blocked with an opaque card. The red dashed lines shows the correspondence between the diffraction maxima in cases (a) and (c).

The next step is to observe the diffraction pattern formed by a wide, approximately parallel beam of green light incident on the CD surface. This can be done by using an overhead projector and a green filter. In order to minimize the scattered light in the room, we placed an opaque card with a 7-cm circular aperture on the overhead projector and a green filter above it. The experimental setup and the observed diffraction pattern is shown in Fig. 2(a).

Two separate concentric circles and a central bright spot are clearly visible. One might think that:

1. the central spot comes from simple reflection from a CD (zero-order maximum), and that
2. the two concentric circles are first- and second-order diffraction maxima.

The first part of this explanation is correct, but the second part is not. The well-known expression for a diffraction grating

$$d \sin \theta_N = N \lambda$$

may be used to determine that for green light ($\lambda \approx$ 550 nm) incident on the CD (d = 1600 nm), the first- and the second-order maxima should be seen at approximate angles of 20° and 45°. This clearly does not agree with the experimental observations.

Performing simple measurements, one can show that both green circles appear at angles that are close to 20°. So, is it possible that both circles belong to the first-order diffraction maximum?

The answer to this unexpected question can be found by first trying to understand what goes on in a plane that is perpendicular to the screen and bisects the circles. Experimentally, this means covering the CD with a black paper mask having a radial aperture as shown in Fig. 2(b). The resulting diffraction pattern when all but the radial strip on the left side of the CD is masked is shown in Fig. 2(c). Two diffraction maxima can be observed, one on each side of the central reflection. By comparing the photos in Fig. 2(a) and 2(c), one can see that the left-hand and right-hand maximum in Fig. 2(c) appear at the posi-

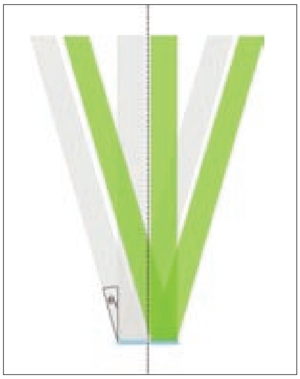

Fig. 3. Two sets of diffraction maxima (zero and first order) are formed in the plane through the CD diameter when monochromatic light is incident on a CD. For clarity, one set is shown in gray.

Fig. 4. The appearance of a magenta color in CD "rainbow." For clarity, only the red-green-blue light components and only half of the first-order maxima are shown.

tions that correspond to outer and inner diffraction ring in Fig. 2(a), respectively. One can show this in the classroom by marking the diffraction maxima (Fig. 2[c]) on the whiteboard and then remove the mask. If the aperture had been extended over the diameter of the CD, two sets of diffraction maxima would have appeared as shown schematically in Fig. 3. It is important to note that beyond a certain distance from the CD, two maxima that originate from the same part of the CD appear on opposite sides of the symmetry axis.

Figure 2(d) shows the diffraction pattern obtained on the screen if the right half of the CD is covered with opaque paper. The result can be mentally constructed from the previous case by rotating the radial aperture through 180° and following the corresponding diffraction maxima. In addition, the same problem can be understood by using the picture in Fig. 3; if the right-hand part of the CD is covered with black paper, the inner left and outer right maximum will disappear. This is consistent with observations [see Fig. 2(d)]. The diffraction pattern obtained from the entire CD surface can be mentally constructed by rotating the two-dimensional diffraction patterns from Fig. 2 through 360°.

From here the explanation of the diffraction patterns obtained with the white light is quite straightforward. The same story, as explained above, now repeats for each color in the spectrum. Taking into account that diffraction maxima for light with larger wavelength appear at larger angles, the separation of the white light into a rainbow of colors with a CD is not a mystery any more.

The only "mystery" that still needs to be explained is the appearance of the magenta band in Fig. 1(a). Of course magenta is obtained as a combination of blue and red light and is not found in the white light spectrum. It is easy to show how this happens in our case if the graphical analysis presented in Fig. 3 is extended to include both red and blue (see Fig. 4). Note that if half of the CD is covered, there is no longer any overlapping of red and blue and the magenta band disappears, as observed experimentally [Figs. 1(a) and 1(b)].

Conclusion

Besides their spectacular visual aspect, rainbow-like spectra produced by diffraction of white light by a CD offer an excellent classroom opportunity for students to practice, or to learn from their teacher, how physics works. As shown in this paper, building a coherent qualitative explanation of their surprising properties is not a trivial task. To get it done, it is necessary to start with a simple quantitative model for the behavior of monochromatic light and then apply the knowledge gained to explain qualitatively behavior of white light that gives rainbow-like spectra.

References

1. P. J. Ouseph, "CD rainbows," *Phys. Teach.* **45**, 11–13 (Jan. 2007).
2. R.White and R. Gunstone, *Probing Understanding* (The Falmer Press, London, 1992).
3. F.M. Goldberg and L.C. McDermott, "An investigation of student understanding of the real image formed by a converging lens or concave mirror, " *Am. J. Phys.* **55**, 108–119 (Feb. 1987).
4. P. Gluck reports an "amusing stunt" when exploring chromatic aberration of a transparent CD acting as a lens. When the central hole of the disk is covered with one finger, a shadow of the finger on the wall or screen has a bright spot in the middle. See P. Gluck, "Compact disk optics," *Phys. Teach.* **40**, 468–469 (Nov. 2002).

PACS: 01.50.My, 42.00.00

Gorazd Planinšič *received his PhD in physics at the University of Ljubljana and is currently an associate professor and chair of a Physics Education course at the Faculty for Mathematics and Physics, University of*

Ljubljana, Slovenia. His research interest is development of active learning approaches with the emphasis on didactical use of experiments. He is co-founder and collaborator of the Slovenian hands-on science centre The House of Experiments. **gorazd.planinsic@fmf.uni-lj.si**

Adrian Corona *holds an MSc degree in physics and is an assistant professor at the Facultad de Ciencias Físico Matematicas of the Benemérita Universidad de Puebla, México. He is interested in improving students' scientific thinking in physics laboratories and in online physics learning.* **acorona@fcfm.buap.mx**

Josip Slisko *holds a PhD in philosophy of physics and is a full professor of physics and physics education at the Facultad de Ciencias Físico Matematicas of the Benemérita Universidad de Puebla, México. He is a member of the Sistema Nacional de Investigadores (level II). His research interest is students' construction of explanatory and predictive models of physical phenomena. Since 1993 he has been organizing the International Workshop "New Trends in Physics Teaching."* **jslisko@fcfm.buap.mx**