

Resolving Spectral Lines with a Periscope-Type DVD Spectroscope

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Observing spectra is an effective way to stimulate students' interest in light and color and, further, to the world of atoms and molecules because it serves as an introduction to spectroscopy. Hence, various educational tools have been developed to observe spectra at the secondary-school level (1–6). In tertiary education, CCD array spectrophotometers, or fiber-optic spectrophotometers, have been recently recognized as useful tools at undergraduate level (7–11). This kind of spectrophotometer is easy-to-use and gives UV–vis spectral charts readily and instantly. While these commercial instruments are smaller and cheaper than older alternatives, it is still not usually possible to provide a set of them for a whole class.

Recently we described a DVD spectroscope that can be made at low cost using common materials (12). This spectroscope is easy-to-make and provides clear and high resolution spectra; it can readily resolve mercury's yellow spectral lines at 577 and 579 nm. This is because a DVD has recording tracks spaced by $0.74\text{ }\mu\text{m}$ (13), that is, ca. 1350 lines/mm, which serves as a reflective grating and is much denser than that of a compact disk ($1.6\text{ }\mu\text{m}$: 625 lines/mm) (6). However, a disadvantage of that spectroscope is that light is collected through a slit that is oriented nearly perpendicular to the viewing angle. It would become much easier to observe spectra if the light that enters from the front of the instrument were captured. Up to this time, CD and DVD spectroscopes have been restricted to qualitative observations. If we could analyze the observed spectra numerically and quantitatively, the spectroscope would become more useful not only in chemical education but also in the wide range of science education.

In this article, we report a new type of DVD spectroscope, the periscope-type, and the numerical analyses of the emission and absorption spectra observed by the spectroscope. Our goal was to develop a high-resolution spectroscope system that can be made using materials and software that can be obtained readily and cheaply. In other words, we aimed at making a personal high-resolution "spectrometer" at a cost of only 1 or 2 U.S. dollars plus a PC, spreadsheet software, and a digital camera. We also explored the resolution of this spectroscope and determined that we could resolve the characteristic Na D lines, at 589.0 and 589.6 nm, in a flame test.

The Periscope-Type DVD Spectroscope

To capture the light from the front of the instrument, we put a small, thin mirror between the slit and the DVD; we call it "periscope type". We used an eighth part of DVD to make the spectroscope small and easy-to-handle. We also reconsidered the diffraction condition of the DVD spectroscope (14). Based on the result, we modified the DVD angle and the position of the slit so that spectra can be observed just in front of the light

axis from the viewing window. The full-sized paper pattern and construction method of the periscope-type DVD spectroscope are available in the online supplement or as a PDF file by sending an email to the author. The spectroscope body is made of a sheet of card stock typically found in manila folders. As a mirror, we used a thin mirror sheet made of aluminum-evaporated film. The sheet was cut to ca. $15\text{ mm} \times 15\text{ mm}$ square pieces and one piece was glued inside the spectroscope. Any small mirror that is thinner than ca. 2 mm with a similar dimension, such as an acrylic mirror, can be used.¹ The remainder of the construction method is the same as previously reported (12). Through these modifications, the spectrum observation and the spectroscope handling have become easier than with the previous design.²

A schematic side view of the periscope-type DVD spectroscope, arranged to take photographs of absorption spectra of solutions, is shown in Figure 1. However, this arrangement can be modified: The cell can be removed to observe emission spectra of the light source and the camera is not necessary to observe spectra by eye. If another colored transparent material replaces the solution, its absorption spectrum can be observed. A fluorescent lamp is convenient as a light source to observe absorption spectra because it can serve as a wavelength standard (see below). Any other white light, such as an incandescent lamp, can also serve as a light source for absorption experiments.

To attach a digital camera to the spectroscope, it is recommended that a round viewing window of diameter slightly less than the lens body be cut (see the online supplement). Then the spectroscope can be supported by the tension of the card stock. A compact digital camera is convenient for this purpose. In this study, Canon PowerShot SD300, which goes by the name of IXUS 40 in Europe and IXY Digital 50 in Japan, was used. Fixing the camera to a tripod, we can take photographs of spectra more clearly and sharply than those reported before (12).

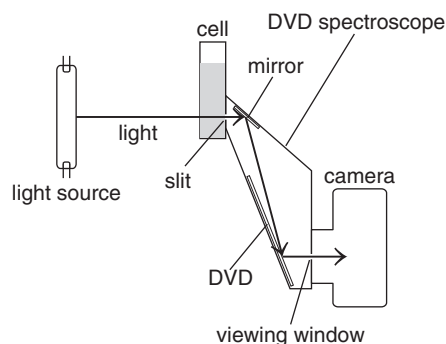


Figure 1. A schematic side view of the periscope-type DVD spectroscope arranged to take photographs of absorption spectra of solutions.

Digitization of the Observed Spectra and Numerical Analysis

A public domain image processing and analysis software NIH Image is available from a free public source (15) and is used in the field of biology and medical sciences. This software has a function to draw a cross-sectional view of a certain area of an image file: Plot Profile command. This procedure derives RGB or gray values of each pixel of the image file and can be used to digitize the observed spectra. If an area with a certain width is selected, this procedure gives average values across the width to improve its S/N ratio. These numerical data can be saved as a text file using Export command. Once the text file is obtained, the data can be analyzed numerically using conventional spreadsheet software. The original NIH Image is for the Macintosh platform, but has been transformed to the Microsoft Windows platform as Scion Image by Scion Corporation (16). The Macintosh version of Scion Image is also available at the same site. Commercial scientific graphing software, such as Origin of OriginLab Corporation, also has a similar function.

The detailed procedure of the digitization by Scion Image is as follows (17):

1. Using graphic software such as Photoshop (Adobe Systems Inc.), Paint Shop Pro (Corel Corporation), or any equivalent tool rotate the spectrum image so that the spectral lines are as nearly perpendicular as possible.
2. Convert the color image to the grayscale image at 8 bit/channel.
3. Select a certain area to analyze and save it as a new BMP file.
4. Open the BMP file using Scion Image.
5. Use Edit-Select All command or Ctrl+A command to make a whole cross-sectional view of the image file. You can also select an area to get numerical data.
6. Use Analyze-Plot Profile command to make cross-sectional view of the selected area. Its graphic image will be shown on the screen.
7. Use File-Export command to save the profile as a numerical data: The data are saved as a text file with a certain file name.

The text file so obtained can be imported for analysis to a spreadsheet such as the free Open Office Calc (18), Microsoft Excel, or others. The result for the spectrum of a fluorescent lamp is shown in Figure 2. A photograph of the observed spectrum is shown in Figure 2A. The white rectangular area shows where numerical data were derived. To calibrate the wavelength, we correlated the pixel position and the wavelength of mercury lines at 404.7, 435.8, 546.1, 577.0, and 579.1 nm (19) using linear fitting function of Excel. As is shown in Figure 2C, an excellent linear correlation between the pixel position and the wavelength was obtained. Once the slope is determined, it can be applied without any modification or with a slight modification if the same combination of the spectroscope and the digital camera is used. The spectral chart of a fluorescent lamp is shown in Figure 2B. As shown in the inset, yellow lines of Hg at 577 and 579 nm were distinctly separated. This chart also shows that the observed spectral lines are unexpectedly sharp: the FWHM of the 577 and 579 nm lines was ca. 0.7 nm.

Emission Spectra

Spectra of Discharge Lamps

The spectral chart of a hydrogen discharge lamp obtained in the same manner is shown in Figure 3A. The wavelength axis was calibrated using the positions of H_{α} (656.3 nm), H_{β} (486.1 nm), H_{γ} (434.0 nm), and H_{δ} (410.2 nm) (19). As shown in the figure, a tiny but apparent peak at 397.0 nm was revealed: this peak should be attributed to the H_{ϵ} line (19).

For a helium discharge lamp, the spectral chart shown in Figure 3B is obtained. Several spectral lines that can be hardly seen by naked eyes or on the photograph were clearly revealed on the chart. They were attributed to the He atomic lines (19). Those results clearly show the advantage of the numerical analysis.

The wavelength axes of those spectral charts were calibrated with the literature data (19) of the spectral lines. However, the wavelength calibration can be independently done by using Hg lines of a fluorescent lamp as the wavelength standards; it can be done by mixing slightly the fluorescent lamp's light with the target light.

Spectrum of the Sun

The sun spectrum obtained in a similar manner is shown in Figure 4. (CAUTION: *Do not observe the sunlight directly. It*

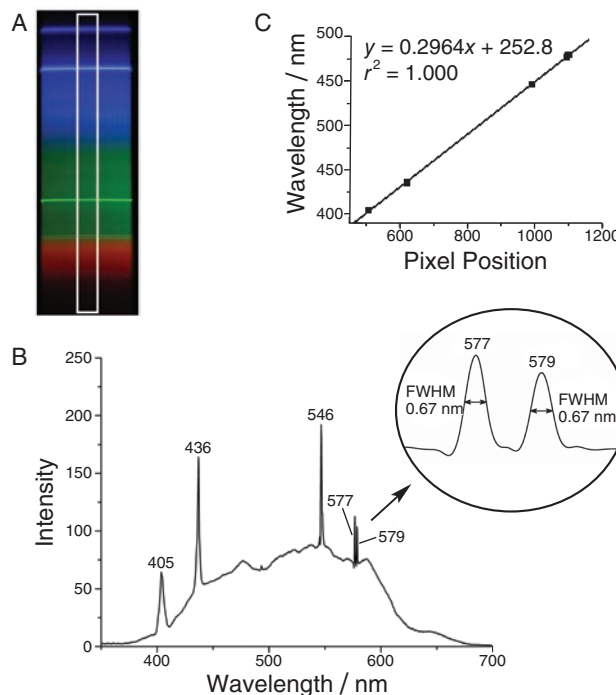


Figure 2. Numerical analysis of the spectrum of a fluorescent lamp: (A) a photograph of the observed spectrum: the rectangular area was analyzed; (B) spectral chart of the lamp obtained as described in the text; and (C) calibration line of the wavelength axis.

will damage your eyes. The light from blue sky, bright cloud, or bright buildings is good enough to observe the sun spectrum). The inset shows the detailed structure of the spectrum around the 520 nm region. As is shown in the figure, many Fraunhofer lines were observed as absorption peaks. The wavelength calibration of the spectral chart was done with several steps to improve its accuracy: At first, the previously determined slope was used (Figure 2C). Since the Na D line was evidently observed in the orange region, the position of the observed Na D line was used as the origin and was fixed at 589.0 nm (19). The first-approximation wavelength axis was thus determined. Using this wavelength axis, it was found that H_α , H_β , and H_γ lines had been observed. Then, the wavelength axis was re-calibrated using Na D, H_α , H_β , and H_γ lines. To obtain a more reliable wavelength axis, we applied a third-order polynomial curve, $\lambda_p = I + C_1p + C_2p^2 + C_3p^3$, where λ_p is the wavelength of pixel p , I is the wavelength of pixel 0, and C_1 , C_2 , and C_3 are the first, the second, and the third coefficients, respectively. This method is the one applied to a CCD array spectrophotometer (20). The resulting spectral chart is shown in Figure 4. From this chart, it was found that the Fraunhofer lines due to Fe, Mg, and Ca (21) were also observed. The observed lines and their assignment are summarized in Table 1. This table shows that those experimentally obtained wavelengths of the Fraunhofer lines are in good accordance with the literature (19, 21).

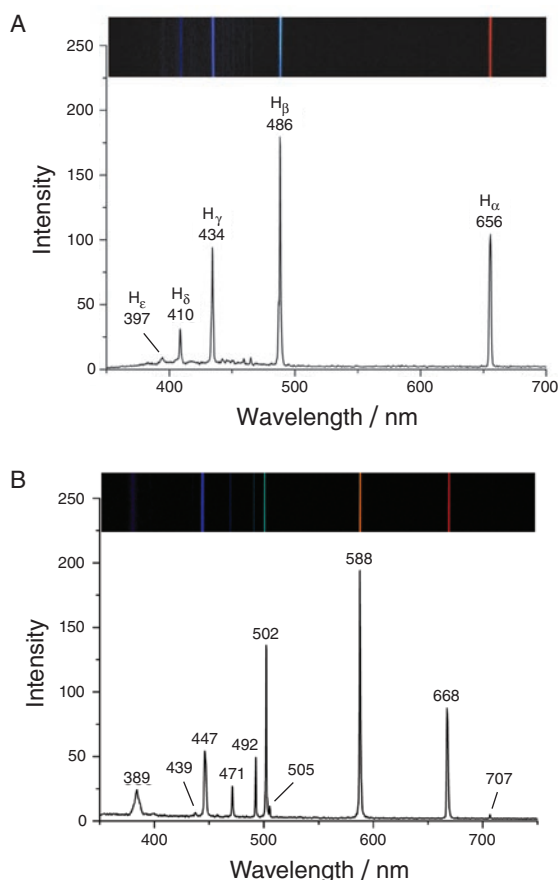


Figure 3. Examples of the spectral charts obtained by using the DVD spectroscope and the method described in the text: (A) a hydrogen discharge lamp and (B) a helium discharge lamp.

Application of the DVD Spectroscope to Chemical Spectroscopy

In the field of chemical education, absorption spectra of colored solutions and emission spectra of flame tests should be of much interest. These spectra are easily observed by the DVD spectroscope, and the spectral charts show clearly the capability of the spectroscope. Typical examples are discussed below. As an application of common materials to chemical spectroscopy, an excellent and interesting method was reported recently in this *Journal*; beautiful and fine fluorescence spectrum of iodine was observed by using a green laser pointer as an exciting light source and a digital camera as a recording equipment (22).

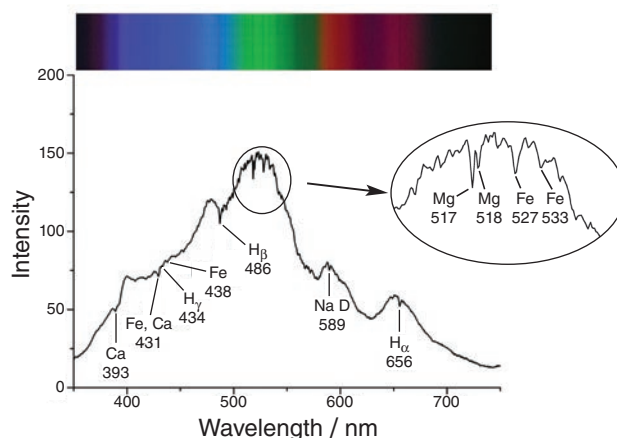


Figure 4. A spectral chart of a sun spectrum observed by the periscope-type DVD spectroscope. Wavelength axis was calibrated using a third-order polynomial.

Table 1. Fraunhofer Lines Observed by the DVD Spectroscope and Their Assignment

Line Position/nm		Difference	Assignment	
Observed	Literature		Element	Line
393.63	393.37	0.26	Ca	K
430.61	430.78	-0.17	Fe, Ca	G
434.02	434.05	-0.03	H	G' (H_γ)
438.58	438.36	0.22	Fe	e
453.26	452.86	0.40	Fe	
486.10	486.13	-0.03	H	F (H_β)
488.77	489.15	-0.38	Fe	
492.04	492.05	-0.01	Fe	
495.62	495.76	-0.14	Fe	c
516.92	517.27	-0.35	Mg	b ₂
518.10	518.36	-0.26	Mg	b ₁
526.89	526.96	-0.07	Fe	E ₂
532.66	532.81	-0.15	Fe	
589.55	589.30	0.25	Na	D
656.53	656.28	0.25	H	C (H_α)

NOTE: Literature data and assignments from refs 19 and 21.

Absorption Spectrum of a Colored Solution: KMnO_4 Aqueous Solution

The deep purple color of KMnO_4 aqueous solution is familiar to chemists. This color arises from the absorption bands in the green region owing to the ligand-to-metal charge-transfer transitions (LMCT) (23, 24). A schematic side view of the apparatus setup to observe absorption spectra is shown in Figure 1. A fluorescent lamp was used as the light source because its Hg lines serve as the wavelength standard. A spectrum of deionized water was used as the reference. The exposure condition was fixed so that the absorbance A at a certain wavelength can be directly calculated as $A = -\log(I/I_0)$ using a spreadsheet, where I and I_0 are intensity for the sample solution and the reference, respectively. The result for the KMnO_4 solution is shown in Figure 5A. Five absorption bands were observed at 491, 508, 526, 544, and 565 nm, which is in good accordance with the literature (24). A reverse band was seen at 546 nm because the Hg line at 546 nm that was used as the wavelength standard could not be completely cancelled out. Figure 5B shows the spectrum observed for the same solution using a commercial UV-vis spectrophotometer Jasco V-550. Good agreement is clearly seen for the peak shapes and peak positions.

Emission Spectrum of Flame Test: Sodium D Line

Sodium chloride was dissolved in a methanol-water mixture. This solution was ignited in a crucible. Its emission spectrum observed by the DVD spectroscope is shown in Figure 6A. Only a sharp peak was observed at 589 nm and assigned to the Na D line (19). The wavelength calibration was done by mixing the fluorescent lamp's light with the flame test. The spectrum in Figure 6A was the one photographed without the fluorescent lamp's light after the wavelength calibration had been done. Although similar spectra of flame tests can be readily obtained using CCD array spectrophotometers (10), this DVD spectroscope has the advantages of low cost and personal involvement of the experimenter. It should be noted, however, that a combined use of the DVD spectroscope and the CCD array spectrophotometer can be effective for an educational purpose of teaching the principles and nature of spectroscopy. The two instruments share their essential elements: a slit with a particular width, a grating for dispersing the light, and a detector (a CCD array for the commercial spectrometer and a digital camera for the DVD spectroscope) (20).

Although the Na D line looks sharp in Figure 6A, closer examination of the line revealed that it consisted of a peak at 589.0 nm and a shoulder around 589.6 nm. This fact stimulated us to think that the D line might be resolved using this simple spectroscopy. We tried to improve the resolution by making the slit narrower and sharper. That was done by using a pair of razor blades as the slit. At first we took a photograph of the spectrum using a wide-angle lens condition as usual to cover whole region of the visible light. The D line was not resolved although the shoulder became more apparent. This result should be attributed to a fact that the digital camera's CCD has only a limited number of pixels. Considering this fact, we took a photograph on the telescopic lens, that is, $3\times$ zoom condition, to expand the D line region. As shown in Figure 6B, the D line was resolved to two lines, D_1 at 589.6 nm and D_2 at 589.0 nm. It should be noted that the expansion of the photograph inserted in Figure 6B does not coincide with the chart. The FWHMs of those lines were less

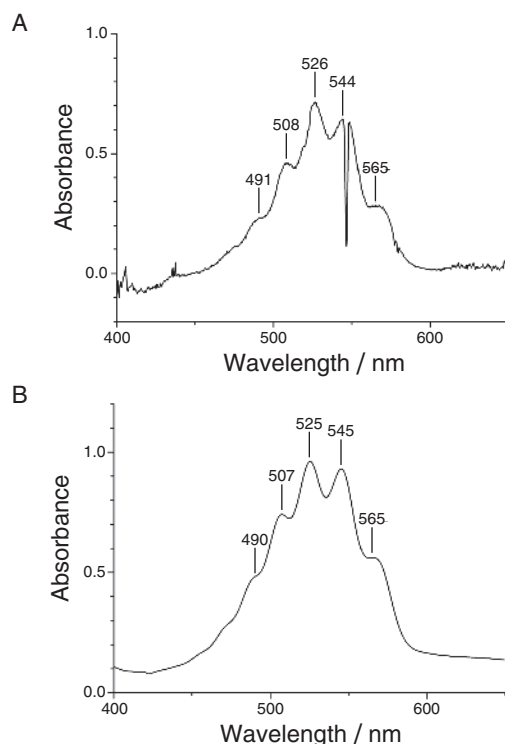


Figure 5. Absorption spectra of KMnO_4 aqueous solution: (A) by the periscope-type DVD spectroscope and (B) by a commercial UV-vis spectrophotometer.

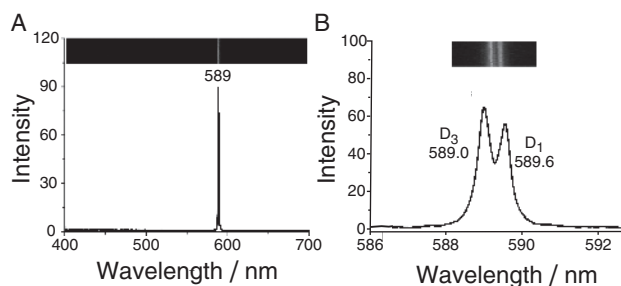


Figure 6. Emission spectra of sodium flame test observed by the periscope-type DVD spectroscope: (A) whole region observed by the usual method and (B) resolving D lines by using razor-blade slit and zoom lens. (The horizontal expansion rate of the photograph is not coincided with the chart.)

than 0.5 nm. This result clearly shows the promising potentiality of the periscope-type DVD spectroscope as a cost-effective science education tool.

Hazards

Do not observe the sunlight directly as it is harmful to your eyes. If the reflected light is painful or difficult to look at, look away at once. Potassium permanganate is a strong oxidant and will discolor skin and stain clothes. Methanol is highly flammable and may be hazardous if inhaled, ingested, or absorbed through skin.

Summary

We improved the design of DVD spectroscopy and made it easy to capture light and handle absorption spectra. Using the periscope-type DVD spectroscopy, we can observe and photograph visible spectra easily and clearly. The spectra photographed using a digital camera were digitized using software that is available from a free public source and were numerically analyzed using a conventional spreadsheet. Spectral charts of the emission spectra of a fluorescent lamp, discharge lamps of hydrogen and helium, sunlight, Na flame test, and the absorption spectrum of KMnO_4 aqueous solution were reported. Such charts revealed the existence of small peaks that are hardly seen by naked eyes or photograph. For the sun spectrum, many Fraunhofer lines were clearly observed and some of the lines were assigned to Na, H, Fe, Mg, and Ca atomic lines. For the Na flame test, the D line was clearly resolved to two distinct peaks at 589.0 and 589.6 nm by using a pair of razor blades as a slit. Those results show that the periscope-type DVD spectroscopy has the promising potentiality as a cost-effective science education tool.

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Notes

1. Aluminized front-surface mirror on a plastic backing, which can be obtained as a repair part of broken rear-view mirror at most of auto-parts stores, is also a cheap and convenient alternative.
2. It should be noted, however, that the previous design does not lose its advantage as a simple spectroscopy.

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