Quantitative characterization of light through a homemade spectrometer: A STEM project-based learning activity

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This paper introduces students to quantitative spectrometry using a hands-on approach, building a simple, low-cost spectrometer to characterize discrete or continuous light spectra, using a smartphone or laptop camera. This project-based learning activity is performed without any specialized equipment (favoring inclusive education at high school and university levels), and allows students to develop scientific skills through the measurement and characterization of light sources, reinforces technological and engineering skills through the construction of the optical instrument and the analysis of light spectra through free software, and applies mathematical competences through the statistical analysis of data. The project is an inclusive and integrative STEM (Science, Technology, Engineering and Mathematics) activity, building contextualized and quantitative knowledge in these areas.

Keywords: Spectrometry; project-based learning; STEM education.

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1. Introduction

Spectrometry, originally thought as the analysis of the interaction of radiation with matter with changing wavelength, but understood nowadays as the determination of the characteristics of any quantity as a function of wavelength or frequency, is one of the most relevant techniques to characterize a system, and as such, faces teachers with the challenge of engaging students in its learning, due to the complexity of experimental equipment required to characterize light sources, which not all institutions can afford. This situation opens the possibility of designing inclusive project-based learning activities in which students can develop or reinforce all STEM (Science, Technology, Engineering and Mathematics) abilities.

Taking into account that one of the main objectives of STEM education is increasing the comprehension of how things work, and favor innovation through the use of scientific knowledge and the application of technology [1], the design of low-cost instruments to characterize everyday phenomena using resources available at any institution (with the appropriate application of technological tools), has shown great potential to develop the skills and abilities required by critical thinkers in STEM [2].

Specifically, the characterization of light sources through a spectroscope sets the opportunity to engage students in the main processes of science and engineering: construction, tune-up and characterization of a device with a specific objective, data taking and processing through mathematical or statistical algorithms, and interpretation of results in terms of scientific models. Taking into account that spectroscopy has found application in many fields, and has been used, for instance, to study the atomic structure through the determination of emission and absorption spectra [3], for the analysis of chemical structures, the investigation of chemical equilibrium and the kinetics of chemical reactions [4], for environmental analysis to determine the acidity of water or the presence of metallic compounds in a sample [5,6], and to determine the chemical composition or the surface temperature of stars [7], spectroscopy has become a very versatile analysis tool in many disciplines, with the potential to be used in the STEM classroom to favor interdisciplinarity.

Nevertheless, a precision spectrometer is an expensive device which many institutions can not afford, and this situation has raised different experimental designs to supply this need and use spectrometers for different applications [8-13], making spectroscopy an inclusive activity in STEM classrooms. This approach could be very enlightening for students, who can understand the physics behind the device used for a specific purpose taking a hands-on approach, which improves student involvement and has proven to be an effective instructional strategy [14,15].

When trying to implement the aforementioned experimental designs in STEM courses, despite their usefulness and applicability, students were confronted with the problem of finding materials with similar dimensions or characteristics to assemble the device and take measurements, and teachers were concerned about how to characterize the observations made with the spectrometer and not merely observe the spectra, without taking any quantitative measurement, as almost all previous approaches did. To alleviate this issues, we have used black cardboard and a small part of a DVD-R, to build a simple foldable spectrometer to capture spectra of different light sources through a smartphone or webcam. Additionally, the spectra were analyzed quantitatively using the Tracker [16] free video analysis and modeling tool, capable of quantifying the brightness and number of pixels in red, green, and blue (RGB) of a line profile [17], helping students to analyze quantitatively the wavelength of light emitted by any source, using a simple linear calibration which, despite its simplicity, has not been used in previous approaches using homemade spectrometers. In this way, this project-based learning activity allows students to develop different STEM skills, constructing an optical artifact with applications in many disciplines.

This paper is organized as follows. In Sec. 2 we discuss the building process of the spectrometer, emphasizing in the details to care about in order to get a functional device and develop important technical skills in students. In Sec. 3 we present the calibration process of the instrument, in order to establish the validity of experimental results obtained, a fundamental scientific skill for students and professionals in STEM. In this section, we also present results obtained by students for the spectra of atomic sources, and make a thorough characterization of the spectrometer through the determination of its resolving power, a process which motivates students to use statistical tools for data analysis and allow them to assess the precision of the instrument. Section 4 is devoted to the analysis of sunlight using the homemade spectrometer, applying known physical models to their own data, and Sec. 5 presents the conclusions.

2. Building the spectroscope and setting up the experiment: developing technological skills

The first step to perform the project and analyze light sources is to build the spectrometer using black cardboard, a DVD-R, scissors and glue or adhesive tape, materials which make the instrument very affordable, easy to build and suitable for use by any student of any institution. An illustration of the final result can be seen in Fig. 1, where all measurements are given in mm.

When building the spectroscope, students should be careful with the position of the DVD-R, which acts as a diffraction grating, decomposing light coming from the horizontal slit opposed to it. As the DVD-R contains many tracks distributed radially, it is fundamental to place them perpendicular to the slit. It is also important to carefully peel off the label and reflecting layers of the DVD-R, to get a functional

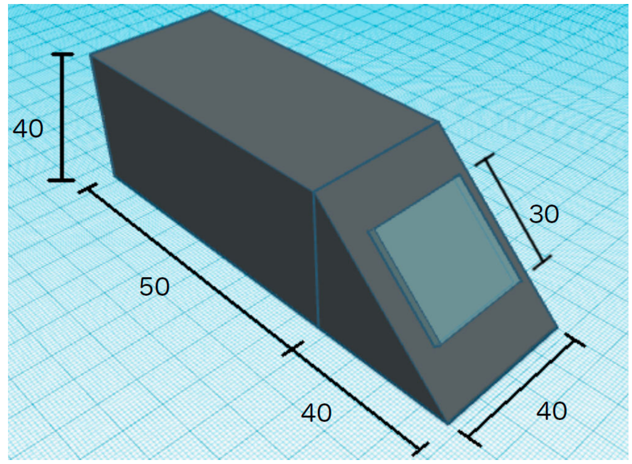

FIGURE 1. Final result of the foldable spectrometer used to perform the experiment, with all measures in mm. A piece of DVD-R is placed in the slanted part of the instrument, and a horizontal slit of approximately 2 mm wide is at the opposite side.

diffraction grating. It is important to note that the specific dimensions of the spectrometer and the position and orientation of the DVD-R, influence the quality of the spectrum obtained, which could appear tilted when observed through a DVD-R not positioned correctly. Another aspect which could change the appearance of the spectrum is the width and sharpness of the slit. All these details and specifications can help students to follow assembling instructions with more precision, and elaborate design briefs for their own projects in a way that is easy to understand and follow, fundamental skills for technology and engineering professionals.

With the spectrometer attached to a laptop or mobile phone camera, facing the DVD-R to its lens, the spectrum of a light source can be captured taking a photo or video using the built-in camera of the device. The analysis of photos or videos can be performed in Tracker [16] (a free software

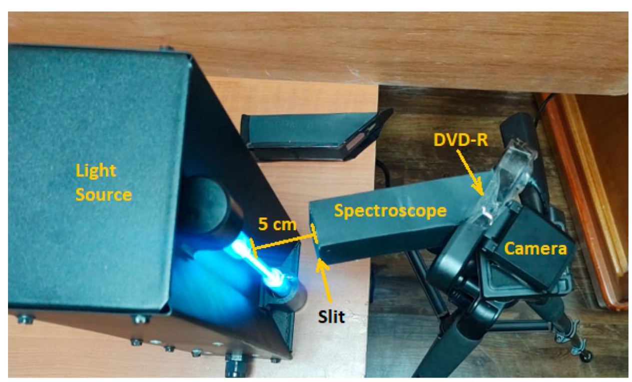

FIGURE 2. Experimental setup for recording light spectra with the homemade spectrometer. The optimum dimensions of the slit are (15.45 ± 0.05) mm long and (2.15 ± 0.05) mm wide, while the portion of the DVD-R not covered by the cardboard is (22.20 ± 0.05) mm long and (20.60 ± 0.05) mm wide. To get the best quality spectra, the DVD-R should be centered in the window of the cardboard, and its tracks should be perpendicular to the slit.

commonly used to get quantitative data from videos or photographs of experiments [18,19]) using the line profile tool. A photograph of the experimental setup is shown in Fig. 2, where the entrance of light and the camera location can be seen, and the optimum dimensions of the DVD-R and slit can be found in the caption, in addition to the specific position and orientation of the DVD-R used to get spectra of the best quality.

3. Data collection and calibration process: developing scientific and mathematical skills

In order to perform a wavelength calibration and get quantitative and meaningful data [20], students can use a compact fluorescent lamp (CFL), which contains at most 5 mg of mercury per bulb, as a light source. The advantage of using a CFL for the calibration process, besides being easily acquired, is that the mercury emission lines of this element are easy to identify and compare with reported data [21].

To calibrate their instrument, students need to find the positions and RGB values of each pixel in a horizontal cross section of the spectrum. This can be done using the line profile tool of Tracker [16], which gives the RGB values of each pixel position along the line profile. Using these results, the average intensity corresponding to each pixel is determined, and a plot of relative intensity as a function of pixel position, as the one shown in Fig. 3, can be done. Taking each peak as a Gaussian bell, students can determine the horizontal position of the center and its dispersion, obtaining the mean pixel position and standard deviation associated with each peak in the mercury spectrum. Using the wavelengths of the mercury emission lines reported by the National Institute of Standards and Technology (NIST) [21], students can perform a regression analysis of a wavelength vs. pixel position graph, as shown in Fig. 4, to get the linear calibration equation which transforms the pixel number N to wavelength λ in nanometers,

$$\lambda = (0.65 \pm 0.01)N + (255 \pm 4). \tag{1}$$

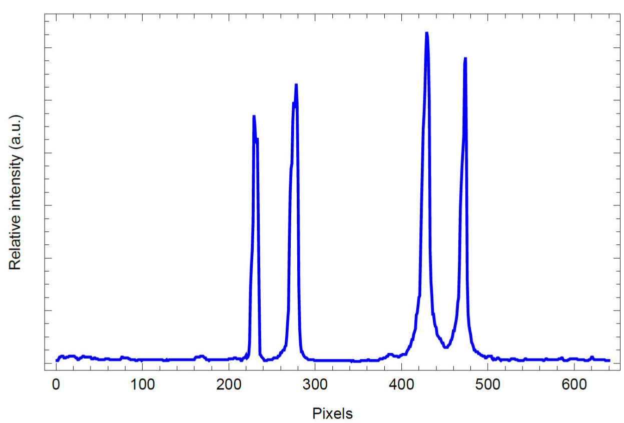

FIGURE 3. Relative intensity as a function of pixel number along the line profile for non–calibrated mercury spectrum.

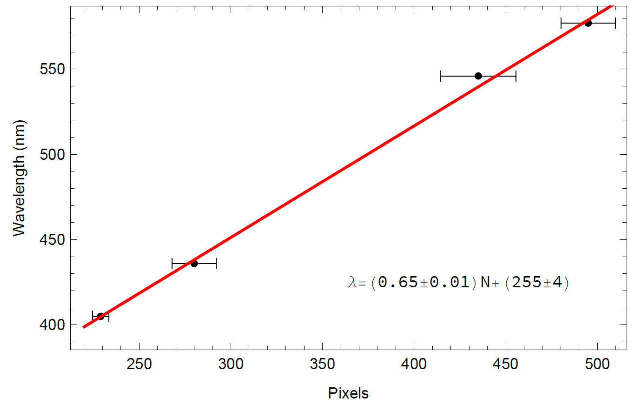

FIGURE 4. Linear calibration obtained from the mercury spectrum in Fig. 3.

This calibration process allows students to apply their knowledge of data preparation and processing through statistical tools, fundamental to all STEM areas. It is important to remark that the linear calibration (1) is acceptable at the 95% confidence level, and would be easy to obtain for undergraduate students, favoring the achievement of the learning goals of the project. Fitting higher order models (quadratic, for example) to the data shown in Fig. 4 would give statistically non-significant parameters, making them inappropriate for the calibration process.

Once the calibration process using the mercury source is done and the equation converting pixels to nanometers was found, students can analyze the spectrum of any light source. Using an equation of the form (1), students convert pixel information, and get plots of relative intensity as a function of wavelength to analyze the spectra of different atoms. It is important to remark that, even though this equation was obtained for pixel numbers between 200 and 500, and wavelengths between 400 and 570 nm (approximately), the prediction intervals for the model show deviations between 2 and 5% for the red part of the visible spectrum, corresponding to a maximum wavelength of 700 nm, when compared with the spectra reported elsewhere, for example in Ref. [22], for the atoms analyzed in this work. These small discrepancies between the predictions of the calibration equation and the expected values of the wavelengths for the visible emission lines, is a strong argument for the use of Eq. (1) for atoms different from mercury. As can be seen from Fig. 8, the differences are stronger in the neon spectrum, for which most peaks are in the red part of the visible spectrum.

Our students have performed the project getting the spectra shown in Figs. 5-8 for mercury, hydrogen, helium and neon, respectively, where the vertical lines in each plot correspond to the reference data from NIST, [22] and the observed spectral lines are displayed in the inset. These results were taken and processed by our students of STEM courses performing the proposed project, and set a huge opportunity to discuss the radiation of light by atoms and the quantum structure of matter [10].

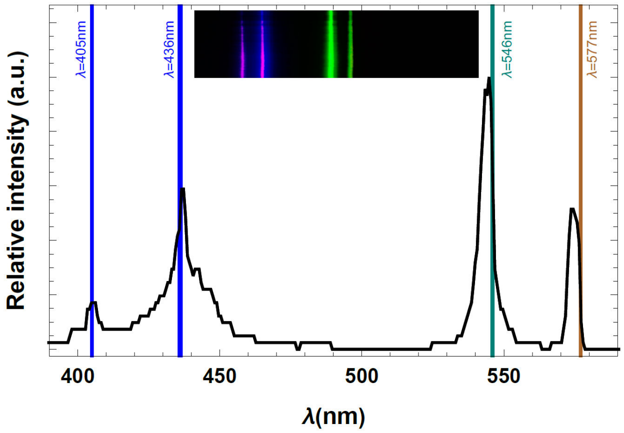

FIGURE 5. Mercury spectrum after conversion of pixel numbers in Fig. 3 to wavelengths in nanometers using Eq. (1).

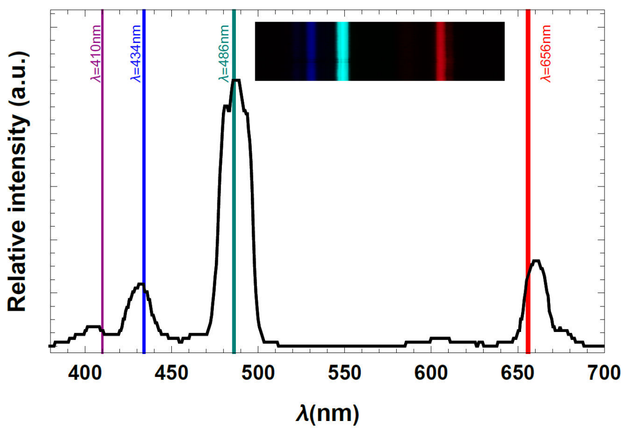

FIGURE 6. Hydrogen spectrum obtained through the homemade spectrometer, converting pixel number to nanometers using Eq. (1).

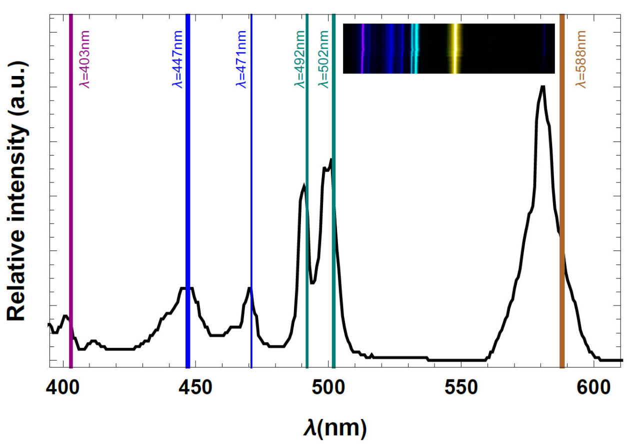

FIGURE 7. Helium spectrum obtained through the homemade spectrometer, converting pixel number to nanometers using Eq. (1).

Through a comparison of the wavelengths of each peak in the measured spectra with the values reported in the literature [21], a deviation of at most 2% is found. This discrepancy is very small and leads to the observation that the homemade

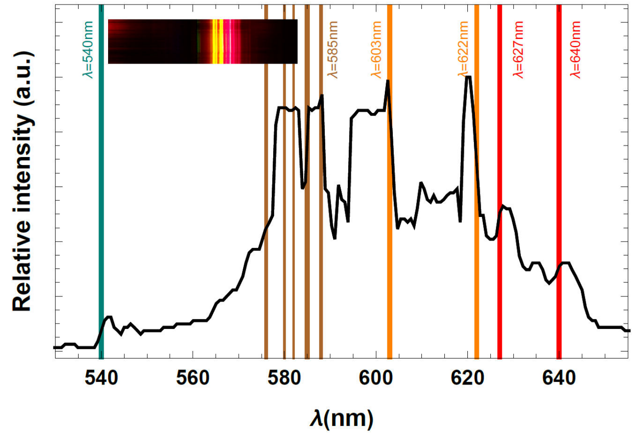

FIGURE 8. Neon spectrum obtained through the homemade spectrometer, converting pixel number to nanometers using Eq. (1).

spectrometer gives results of sufficient accuracy to perform the analysis of different light sources.

In order to further evaluate the quality of measurements taken with their spectrometer, students can find the resolving power of the instrument, defined as

$$R = \frac{\lambda}{\delta\lambda}, \tag{2}$$

where $\delta\lambda$ is the minimum difference in wavelength of two spectral lines resolved by the instrument at a wavelength λ. $\Delta\lambda$ is usually calculated as the full-width at half maximum (FWHM) for diffraction slit spectroscopes [23], and the value of R is used by astronomers to classify the instruments used, where the common criterion states that $R < 1000$ corresponds to low resolution, $1000 < R < 10000$ to intermediate resolution and $R > 10000$ to high resolution spectrographs [24].

As an example, we have found the resolving power of the homemade spectrometer taking the results for the hydrogen spectrum, for which the measured spectral lines wavelengths and FWHMs for each peak are shown in Fig. 9, finding resolving powers of 18, 25, 27 and 48 at measured wavelengths of 403, 428, 486 and 667 nm, respectively. These figures indicate that the homemade spectrometer has a very low resolving power in comparison with astronomical instruments, and this fact could be used to motivate students to discuss the need to disentangle spectral lines and the technology of astronomical instruments such as the Hubble Space Telescope, which includes a spectrograph dedicated to the analysis of large-scale structure of the universe and formation and evolution of galaxies [25], or the James Webb Space Telescope (JWST), a telescope dedicated to analyze the afterglows of the early universe and the formation of galaxies, to mention just a few of its scientific objectives [26].

Another aspect that could be assessed by students is the characterization of intensity measurements with the spectroscope, and the effects of filters in the webcam or mobile cameras, taking into account the decrease in relative spectral intensity which appears in these cameras in the 600 to 700 nm range, corresponding to the red part of the visible spectrum.

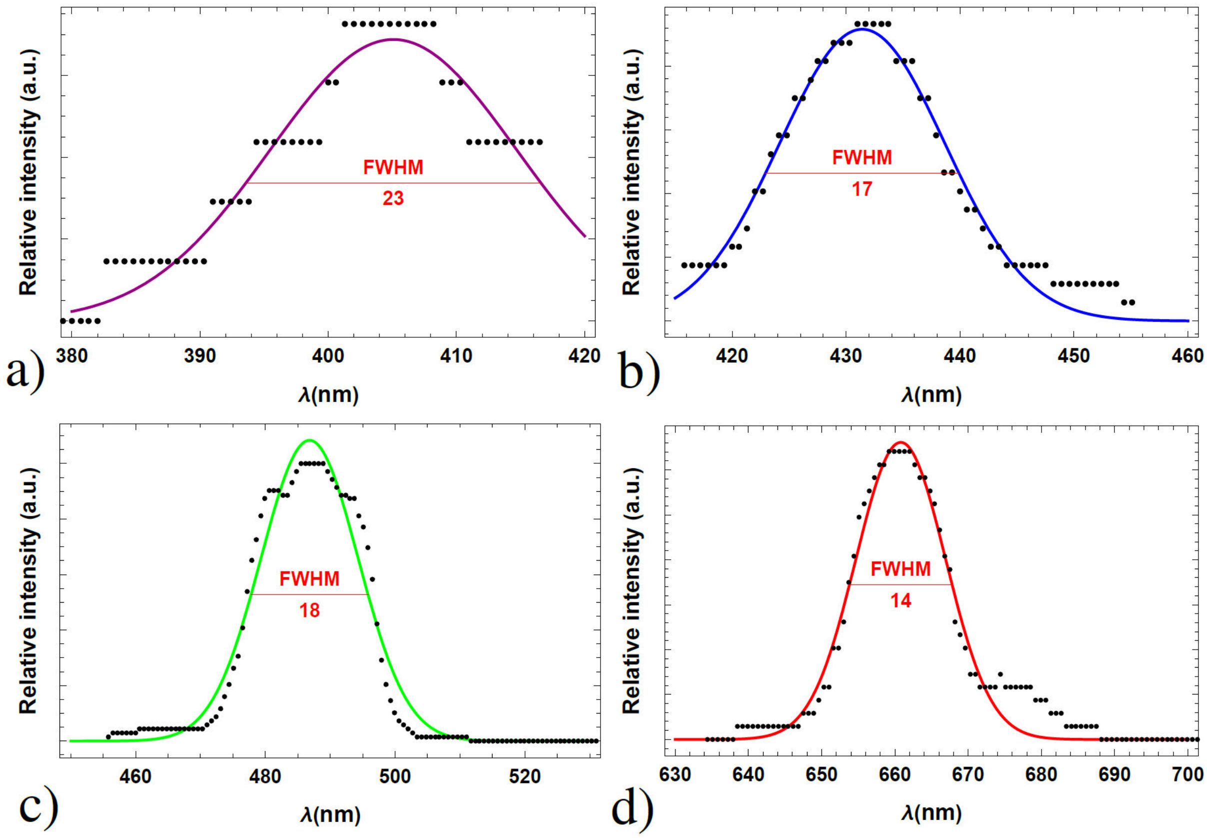

FIGURE 9. Best fits for hydrogen peaks observed from Fig. 6, where the resonance wavelengths measured with the homemade spectrometer are a) 403 nm (violet line), b) 428 nm (blue line), c) 486 nm (green line) and d) 667 nm (red line), and the FWHM for each peak is shown.

This situation poses a challenge over the use of the instrument, which could be solved only through a detailed analysis of the highly non-linear response of the laptop or smartphone camera, the non-linear effects which the compression of graphics files could induce in the measurement, and the response function of the light detector in the camera. As the analysis of these aspects is extremely difficult to perform for high school, freshman or even sophomore students in STEM courses, we recommend avoiding it in the formulation of the project, to preserve the objective of a well-defined outcome suggested in STEM project-based learning [2].

4. Analysis of sunlight spectrum: reinforcing scientific and modelling skills

The spectra analyzed so far, produced by atomic sources, are composed of discrete lines emitted when an electron makes a transition from a higher energy level to a lower one. In this section, students use the homemade spectrometer to analyze sunlight, characterized by a continuous spectrum from which they can estimate the temperature of the Sun through the determination of a model fitting their measured data, reinforcing the application of skills in statistics and modelling, crucial in STEM.

In Fig. 10 we show the sunlight spectrum obtained with the homemade spectrometer (continuous black line) and the blackbody radiation spectrum obtained for this data set, as a continuous red line. In the same graph, we can see the standard solar spectrum [27] as a continuous gray line and its corresponding fit using the blackbody radiation spectrum, as a continuous blue line. In order to fit a blackbody radiation spectrum and students be able to use their data to estimate the surface temperature of the Sun through the application of Wien's displacement law, we have used Planck's law for the energy distribution function of a blackbody, [28]

$$u(\lambda) = \frac{8\pi hc}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]}, \tag{3}$$

where h is Planck's constant, c is the speed of light in vacuum, λ is the wavelength of the radiation, k is Boltzmann constant and T the absolute temperature of the blackbody. As the brightness measurement taken by Tracker is directly proportional to the energy radiated by the light source, we have fitted an equation of a form similar to Eq. (3) for the brightness I_R measured by tracker

$$I_R = \frac{A}{\lambda^5\left[\exp\left(\frac{B}{\lambda}\right) - 1\right]}, \tag{4}$$

with parameters A and B. The physical interpretation of the coefficient A is not important for our purpose of estimating the surface temperature of the Sun, which can be obtained through the application of Wien's law [27],

$$\lambda_{\text{max}} = \frac{b}{T}, \tag{5}$$

where $b = 2.898 \times 10^{-3}$ m · K is Wien's displacement constant and λ_{max} is the wavelength for which the energy distribution function in (3) is a maximum, for which our students obtained a value $\lambda_{\max} = 495$ nm, very close to the wavelength for maximum solar radiation at 500 nm [27].

In Fig. 10, we can see that the measurement taken with the homemade spectrometer for the spectrum of sunlight, is in approximate agreement with the standard solar spectrum for the wavelength range 400 – 580 nm, where the attenuation of relative intensity is not very significant, and the intensity issues described at the end of the previous section can be circumvented. Additionally, as the linear calibration Eq. (1) was obtained from the main lines of mercury, lying in the same wavelength interval, choosing this range for the data analysis improves the reliability of the model obtained.

From the fits of the blackbody radiation spectra performed on Fig. 10, we can see a displacement of the maximum of the graph, and this will give a higher value of the surface temperature of the Sun. More specifically, from the fit to the blackbody radiation spectrum to the data obtained with the homemade spectrometer and using Wien's displacement law (5), our students obtained a Sun surface temperature of (5860 ± 130) K, with a percentage error of approximately 2% with respect to the reported value [29]. The determination of the Sun's temperature with such a small deviation when compared with results obtained using specialized equipment [27], reinforces or reactivates the motivation of students for STEM.

An important remark should be done at this point. Even though the result for the surface temperature of the Sun has little deviation from the accepted result, the reported value has been obtained with the data measured only in the visible part of the electromagnetic spectrum (for which the instrument provides data), and for the wavelength interval for which the linear calibration Eq. (1) has been obtained. It is important to keep students aware of this, to enhance their critical sense about the validity of the results obtained, and to keep their mind open to look for different solutions.

5. Conclusions

We have seen that the homemade spectrometer, the prototype in this project-based learning activity, can be used in STEM courses to characterize discrete light sources, and sets a huge opportunity to develop or reinforce skills in all STEM areas. The instrument is accurate in terms of wavelength, but presents an attenuation in intensity (specially for the red part of the visible spectrum), due to the effect of laptop or mobile phone cameras used by students performing the experiment. The spectral resolution is enough to disentangle discrete lines with separation greater than 10 nm, but lines with smaller separation just overlap. This characteristic allows students to understand the physical processes behind the spectroscope, increasing the comprehension of how things work and favoring innovation.

Students can perform the characterization of continuous light sources as the Sun, and use the measured spectra to understand the properties of blackbody spectrum and determine the surface temperature of the Sun. Even though the result obtained from the blackbody radiation spectrum for the surface temperature of the Sun is very close to the reported data, students should be warned to be critical about the validity of their results.

In this work, we have shown that homemade spectrometers can be used in STEM courses to perform a characterization of both discrete and continuous light sources in such a way that students apply a wide range of skills: design and construction of a prototype, data collection and processing, determination of a physical model which can be validated and from which predictions can be made, use of technology with a well-defined purpose, and assessment of a prototype, the measurement process, the data collected and the results obtained. All these correspond to fundamental skills in STEM, which can be reinforced with this project-based learning activity.

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