Phys316 Exploration 2: *Verifying Stefan-Boltzmann Relationship*

**Background**
The power radiated by a black body of temperature $T$, is given by the Stefan-Boltzmann Law

$$P = \sigma A T^4$$

Where $A$ is the effective radiating area, $\sigma = 5.670 \times 10^{-8} \text{W/m}^2\text{K}^4$, is the Stefan-Boltzmann constant. For a non-ideal blackbody one must correct the relationship by the emissivity $\varepsilon$, which is equal to one for a perfect black body, and less than one for other radiating objects.

We will be investigating the Stefan-Boltzmann law using a tungsten filament lamp. The electrical power consumed by the filament is given by:

$$P_{el} = VI$$

Where $V$ is a constant voltage applied across the filament and $R$ is the resistance of the tungsten, and $I$ is the current across the filament.

**Project Descriptions:** We will be investigating the spectral properties of a tungsten light bulb as the current across the filament is varied. This will result in a change in temperature which will result in an observed spectral shift according to Wien’s Law:

$$\lambda_{max} = \frac{b}{T}$$

Where $b$ is constant of proportionality called Wien's displacement constant, equal to $2.898 \times 10^{-3} \text{m-K}$.

**Preliminary**
1. Sketch a plot of what you believe the intensity as a function of wavelength of a light bulb should look like in the space below? What would happen to that spectrum as the temperature of the bulb is raised?
**Reference Curves**

Every spectrometer has what is called an "instrument response function", or IRF. The IRF refers to how much the spectrometer responds to light across its wavelength range. This response is far from uniform: a spectrometer will produce a different response (here defined as the number of Scope-mode counts produced for a fixed number of photons) at every pixel. The IRF is non-uniform because of the cumulative effects of optical inefficiencies in the light path. These include, but are not limited to:

- Attenuation of light in the fiber optic cable
- Absorbance of light by the mirrors (which varies with wavelength)
- Grating efficiency
- Detector response (the CCD is more sensitive to some wavelengths than others)

The IRF for each spectrometer is unique, and cannot really be measured. However, it is possible to compensate for the IRF. The two common corrections are Relative Irradiance and Absolute Irradiance calculations.

2. If our detector has a bias towards different parts of the spectrum, how might this effect our measurement of source spectrum and temperature?

The spectrometer you are using is an Ocean Optics Red Tide USB650. It has the ability to correct for the wavelength dependence of the instrument using a reference curve from a known temperature source.¹

In your experiment, you must first calibrate your system by measuring the spectrum of a known temperature source. Then you will measure the relative Irradiance spectrum of your tungsten bulb at three different temperatures (voltages). The grating you have measures from 350-1000 nm. Thus the spectrum you measure will be truncated for higher infrared wavelengths and you will not be able to observe the entire Boltzmann distribution of the light spectrum. You will however, be able to identify the wavelength of maximum emission. Using Wien’s law you can then estimate the temperature of your light bulb. We will compare this temperature to the temperature estimated from the power consumption of the light bulb. When you arrive in the lab, do not change the alignment of your iris, light bulb, or fiber optic cable mount unless specifically asked to do so. We have taken great care to align everything so that you will be able to collect data in the limited time available. Any adjustments may result in poor data quality, and inability to complete the project.

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¹ For more information on possible sources of error refer to http://www.oceanoptics.com/technical/systemsensitivity.asp
**Exploration 2: Observing the Temperature Dependence of Blackbody Radiation**

Do not change the alignment of your iris, light bulb, or fiber optic cable mount unless specifically asked to do so. We have taken great care to align everything so that you will be able to collect data in the limited time available. Any adjustments may result in poor data quality, and inability to complete the project.

**Project 1: Calibration of the Spectrometer**

We will correct for the wavelength dependence of our spectrometer system by using the relative Irradiance mode of the spectrometer. Open the Spectra Suite program on your computer. Select a relative irradiance measurement by going to the main menu under File/New/Relative Irradiance Measurement. A new screen will open and should look like the screen shown below.

Connect a blackbody light source with a known color temperature at its output to the spectrometer with an optical fiber assembly. We will be using a calibrated Tungsten-Halogen bulb with temperature of 2960K. We will need to take turns as there is only one calibrated source.

The screen shows the Red Tide usb650 spectrometer is attached to the computer. If you had multiple spectrometers present, you would select the one you wished to use here. Click Next.

The “Set Acquisition Parameters wizard” is now displayed and is shown at the top of the next page. It is important to ensure that the detector is not saturated. Click the “Set automatically . . .” button to adjust the acquisition time such that the detector is not saturated. You may have to hit the button multiple times.
Smoothing will allow you to identify the peak maximum in your data more easily by eliminating some of the random noise in the signal. Set “Scans to Average” to three to improve signal to noise ratio. Click Next.

The “Store Reference wizard” window is now displayed, and is shown below. Click the yellow light bulb to store your reference spectrum. Click Next. You are now finished with the calibration source. Do not close your program or your reference spectrum will be lost.
The “Store Dark Reference wizard” spectrum is now displayed. Remove the fiber optic from the calibrated source by unscrewing it from the connector. Do not touch the end of the fiber optic with your fingers as the oil from your skin can damage the cable. Cover the end of the cable with the blue plastic cap provided. Click the dark light bulb button. Click Next.

The “Store Color Temperature wizard” window opens. Enter the color temperature of the calibrated source. The temperature of the tungsten-halogen bulb used is 2960 K. Click Finish. You are now ready to measure the relative irradiance of your light bulb at various voltages.
Project 2: Observing Wien Displacement Law

The Axis on the graph has been changed to “Irradiance (Relative)”. You can see two tabs; if you click on graph A you will be brought to the scope mode, and observe the un-calibrated signal. You observe that it is remarkably similar to the calibrated source spectrum observed. This should not be surprising as they are both tungsten filaments, though operated under very different conditions. This un-calibrated signal shows you how much the signal is diminished by the grating and optics at both the highest wavelengths and ultraviolet wavelengths. Our relative irradiance modes compensate, although not perfectly, for this bias. It is important that you not saturate the detector. That is why we have included a variable diameter aperture, or “iris” in your system. You will need to adjust the diameter of this iris to avoid saturation at the highest voltages, then open the iris to increase the signal at the lowest voltages. To open the iris slide the silver knob around the ring. Do not change its position laterally or vertically as this will result in a spectral distortion. You may note a rise in the signal at near infrared wavelengths (\(\lambda > 900\) nm). This is due to inefficiencies of the fiber optic cables at these wavelengths. As long as you can observe the wavelength of the maximum value of the intensity, you will be able to observe the spectral shift sufficiently.

1. Describe what you observe with respect to the overall intensity and the distribution of intensity over the visible spectrum. Is the light more concentrated toward the red or the violet end of the spectrum at one temperature as compared to the other?

2. Measure the spectrum at three voltages from 30-120 Volts. Record the voltage and current settings at each position using the multi-meters attached (to wake up the multimeters, press the Range button). Make sure your current measurement is made in the AC Amp mode. Save the spectrum by clicking the disk button directly above your spectrum. Be sure to select a Processed Spectrum Format from the “File Type” drop down menu. Press the Browse button to choose a directory. Name the file with a name descriptive of the voltage level. Press Save, the Save again on the Save Spectrum window, then Close. Repeat for a different voltage levels.

You may plot all of your results on the same axis by opening the processed spectrum into Spectra Suite. Select File/Open/Load Processed Spectrum. Open all of your files. The data files should appear now below your icon of the spectrometer on the Left Side of your program. Plot the data by right clicking on the file name. Select plot as overlay. Select appear in new window for your first file, then select this same window when adding other data as overlay.

3. Make a sketch of your observations for the spectrum of light as a function of wavelengths for at least three different temperatures on the graph paper provided. Do your results appear to agree with Wien’s law?

\[
\lambda_{\text{max}} = \frac{b}{T}
\]

Where \(b\) is constant of proportionality called Wien’s displacement constant, equal to 2.898×10⁻³ m·K.
The distribution of radiant energy as a function of wavelength led Planck, in 1901, to introduce the then radical assumption that energy is emitted in discrete jumps, or quanta, for which he was awarded the Nobel Prize in 1918.

4. Using Wien’s law estimate the temperature of the bulb from your spectrum at the three different voltages.

Project 3: Verifying the power output of a Tungsten Filament

5. Calculate the power consumed by the light bulb for each of the settings used in Project 2. Calculate the temperature you would expect the filament to be at if the bulb acted as a blackbody.

6. Compare your measured spectral temperatures from part 2 to those given by the power consumption of the bulb. Do they compare reasonably well? Discuss any potential sources of error.

Of course the resistance of a real material is temperature dependant and given by:

\[ R(T) = \rho(T) \frac{L}{a} \]

Where \( \rho, L, \) and \( a \) are the resistivity, length, and cross-sectional area of the tungsten filament. The resistivity of tungsten has been well established to have a power law dependence of

\[ \rho(T) = 5.792 \times 10^{-11} \cdot T^{1.209} \]

over a temperature range from 273 to 3655 K, where \( \rho(T) \) has units of \( \Omega \cdot m. \) The emissivity of tungsten over the visibly radiating range from 2000-3555 K, has also been well established

\[ \varepsilon(T) = 1.731 \times 10^{-3} \cdot T^{0.6632} \]
Project 4: Measuring the Temperature of an LED Diode

7. Move your light bulb off to the side. Place the LED flashlight at approximately the same distance from the iris, as your light bulb had been. Try to align the height of your flashlight directly in line with your iris and fiber optic cable. Adjust the iris as needed to obtain a spectrum that is not saturated. Sketch the Relative Irradiance spectrum of your LED on the graph paper provided. What differences do you notice from the tungsten lamp spectrum and the LED spectrum? What causes the shape that you observe for the LED light source?

8. Estimate the “temperature” of your LED using Wien’s law. How does the temperature compare to that of your tungsten lamp?

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