Exp. P-6 Blackbody Radiation

Updated Feb 2019 by A. Azelis, M. Hohlmann

Equipment

Prism Spectrophotometrer Kit	OS-8544
Optics Bench (60 cm)	OS-8541
Spectrophotometer Accessory Kit	OS-8537
Aperture Bracket	OS-8534
Broad Spectrum Light Sensor	PS-2150
Universal DC Power Supply	PD-6505
Mastech Multimeter	MS-8261
Banana Plug Cord	SE-9751
Pasco Airlink	PS-3200
Capstone	UI-5406

Introduction

The spectrum of an incandescent light bulb is scanned by hand using a prism spectrophotometer that measures relative light intensity as a function of angle. A Broad Spectrum Light Sensor is used with a prism so the entire spectrum from approximately 400 nm to 2500 nm can be scanned without the overlapping orders caused by a grating. The wavelengths corresponding to the angles are calculated using the equations for a prism spectrophotometer. The relative light intensity can then be plotted as a function of wavelength as the spectrum is scanned, resulting in the characteristic blackbody curve. The intensity of the light bulb is reduced, reducing the temperature, and the scan is repeated to show how the curves nest with a shift in the peak wavelength.

The temperature of the filament of the bulb can be estimated indirectly by determining the resistance of the bulb from the measured voltage and current. From the temperature, the theoretical peak wavelength can be calculated and compared to the measured peak wavelength

Theory

The intensity (I) of radiation emitted by a body is given by Planck's Radiation Law:

$$I(\lambda) = \frac{2\pi c^2 h}{\lambda^5}\left(\frac{1}{e^{\frac{hc}{\lambda kT}} - 1}\right)$$

where c is the speed of light in a vacuum, h is Planck's constant, k is Boltzmann's constant, T is the absolute temperature of the body, and λ is the wavelength of the radiation.

The wavelength with the greatest intensity is given by Wien's Law

$$\lambda_{max} = \frac{constant}{T} = \frac{.002898\, m \cdot K}{T}$$

Where T is the absolute temperature of the body. The temperature of the blackbody light filament can be calculated using the resistance of the filament while it is lit. The resistivity of the tungsten filament is a nonlinear function of the temperature. The temperature can be calculated using a function that approximates the dependency on resistivity. It can be found in the analysis section of this manual.

The resistance of the filament is found using:

$$R = \frac{V}{I}$$

Where V is the voltage applied to the lamp and I is the current through the lamp. The temperature dependence of the resistance is used to determine the temperature of the hot filament. See the appendix section of this document for an explanation of this process.

Setup

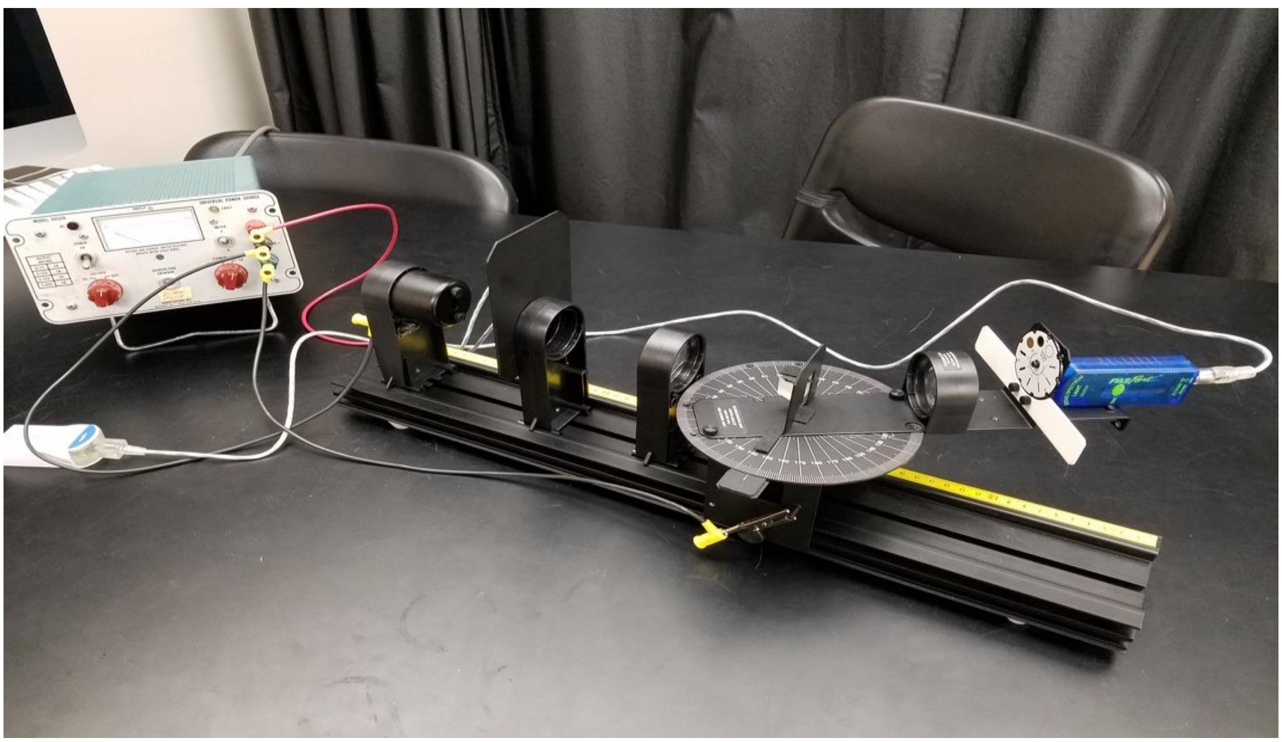


Figure 1: Complete Setup

1. Set up the Prism Spectrophotometer as shown in Figure 1. The light sensor used in this experiment is the Broad Spectrum Light Sensor.

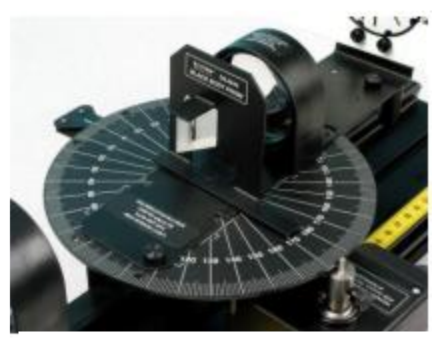


Figure 2: Prism Orientation

2. Check that the prism is shown as in Figure 2 with the apex facing the light source.
3. **Important:** Ground the Spectrometer by attaching one end of an alligator jumper cable to the ground post on the bottom of the spectroscopy table and attaching the other end to the ground of the power supply. This will ground the light sensor itself and provide a stable baseline for the sensor readings.
4. The collimating lens must be 10 cm (the focal length of the lense) from the collimating slits.
5. Plug the Blackbody Light into the DC Power Supply.
6. Setup the multimeter to measure the voltage across the DC Power Supply. **Use the multimeter to monitor the power supply voltage output** as the device's analog meter is not consistently reliable. **Caution:** Never exceed an output of 10 V - otherwise you risk damaging the bulb's filament.
7. Plug the Broad Spectrum Light Sensor into the Pasco Airlink
8. Open Pasco Capstone software. See the appendix for basic instructions on using Capstone if you are not already familiar with it.

Procedure

1. Set the collimating slits appropriately. Set the Light Sensor mask appropriately.
2. Turn on the DC power supply and and monitor it with the multimeter. Set the voltage limit to 60V and current limit to 5A.
3. Turn the current dial to the 10 o'clock position. **Slowly** turn the voltage dial up until the multimeter reads 10 V. **Caution:** If 10 volts is applied to the blackbody light for an extended amount of time, the life of the bulb will be reduced. Only turn on the bulb when taking measurements.
4. Measure the current through the lightbulb using the multimeter and record this value.
5. Look at the light coming from the Blackbody Light Source. Observe the color.
6. Look at the spectrum on the Light Sensor screen. Are all the colors (from red to violet) present?
7. Rotate the scanning arm until the slit on the light sensor mask is to the left of the visible spectrum on the screen.
8. Open a new data collection file in Capstone. Setup the program to measure the Relative Intensity and record data in "Keep" mode. See the appendix for more information on Capstone.
9. Record values of Relative Intensity across the spectrum. Measure in appropriate angular increments over an appropriate range. While rotating the scanning arm, ensure that the prism maintains proper orientation with the apex facing the light source.
10. Repeat steps 3-9 for several lower voltages to measure the spectrum for lower temperatures.

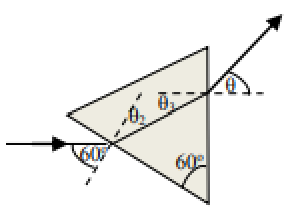
Analysis

1. Using your measurements and the relationship between angle and wavelength as described in the appendix, plot intensity vs. wavelength for each voltage.
2. Does the peak shift toward shorter or longer wavelengths as the temperature is lowered?
3. How does the intensity change as the temperature is changed?
4. What is the temperature of the filament at each voltage? See appendix for details of calculation.
5. Calculate the peak wavelength corresponding to each data set using Wien's law and the temperatures found in step 3 of the Analysis. Do these wavelengths coincide with the peak wavelengths on your experimental intensity graphs?
6. Using the temperatures you previously calculated, plot the theoretical Planck function (intensity vs. wavelength) for each temperature. Fit the data to Planck's Radiation Law.
7. Contrast your measured distributions with the theoretical models. Does the shape of the experimental curve match theory? Can the bulb really be considered a blackbody? **Quantitatively justify!**
8. How did the color of the bulb change with temperature? How did the color composition of the spectrum change with temperature? Considering the peak wavelengths, why is a bulb's filament red at low temperatures and white at high temperatures?
9. At about what wavelength is the peak wavelength of our Sun? What color is our Sun? Why?
10. For the highest temperature, is more of the intensity (area of the intensity vs. wavelength graph) in the visible part of the spectrum or in the infrared part of the spectrum? How could a light bulb be made more efficient so it puts out more light in the visible?

Appendix

Wavelength Calculation

The index of refraction of the prism glass varies with the wavelength of the light. To determine the wavelength as a function of the angle, the relationship between the index of refraction and the angle is determined using Snell's Law at each face of the prism.



$$n = \sqrt{\left(\frac{2}{\sqrt{3}} sin\theta + \frac{1}{2}\right)^2 + \frac{3}{4}}$$

The Cauchy equation provides a formulation of the wavelength dependent index of refraction:

$$n(\lambda) = \frac{A}{\lambda^2} + B$$

Where A and B are specific to the type of glass and are determined experimentally.

doesn't work for angle >= 124

Solving for wavelength results in:

$$\lambda = \sqrt{\frac{A}{n - B}}$$

Where A = 13900 and B = 1.689 for this experiment.

Temperature Calculation

The temperature of the filament can be found after calculating its resistivity r:

$$r = r_o \left(\frac{\frac{V}{I} - 0.2}{R_{bulb}} \right)$$

Where:

- r_o = 5.65 [μΩ-cm] (Resistivity of Tungsten at room temperature)
- V = Voltage [V]
- I = Current [A]
- R_{bulb} = .93 [Ω]

The temperature is then found using a curve fit for the range of interest:

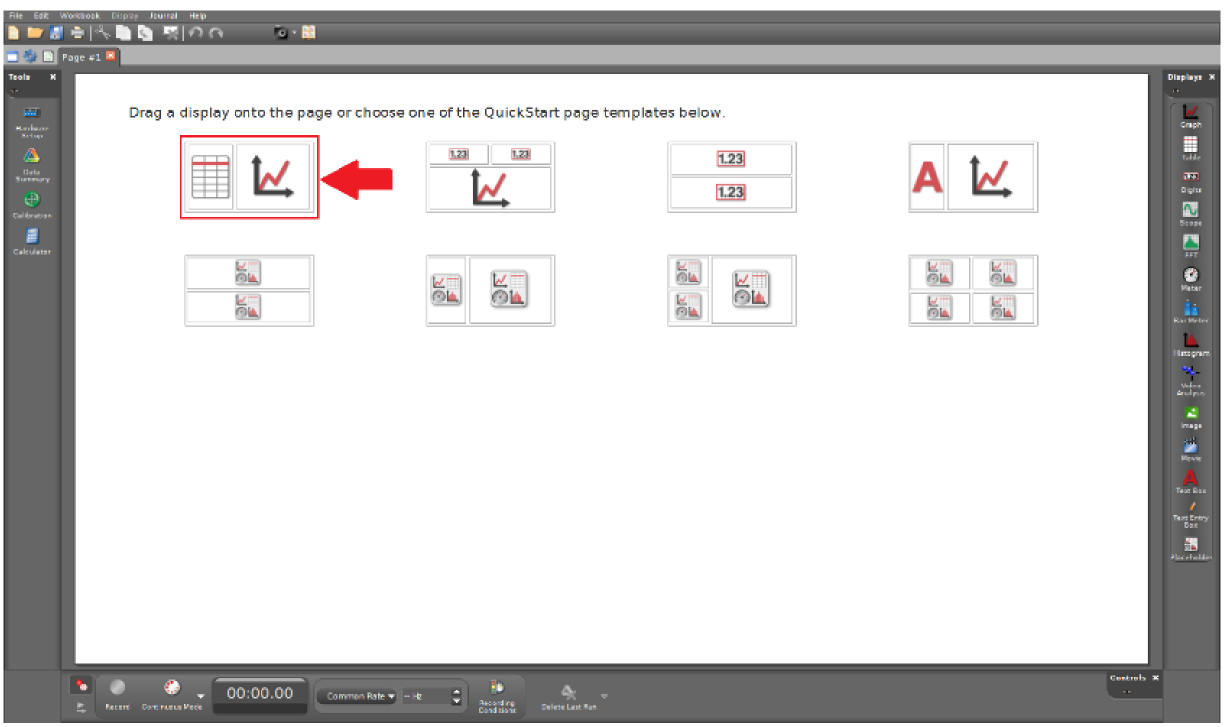
$$T\ [K] = 103 + 38.1r - .095r^2 + (2.48 \times 10^{-4})r^3$$

Values are tabulated in the following table (next page):

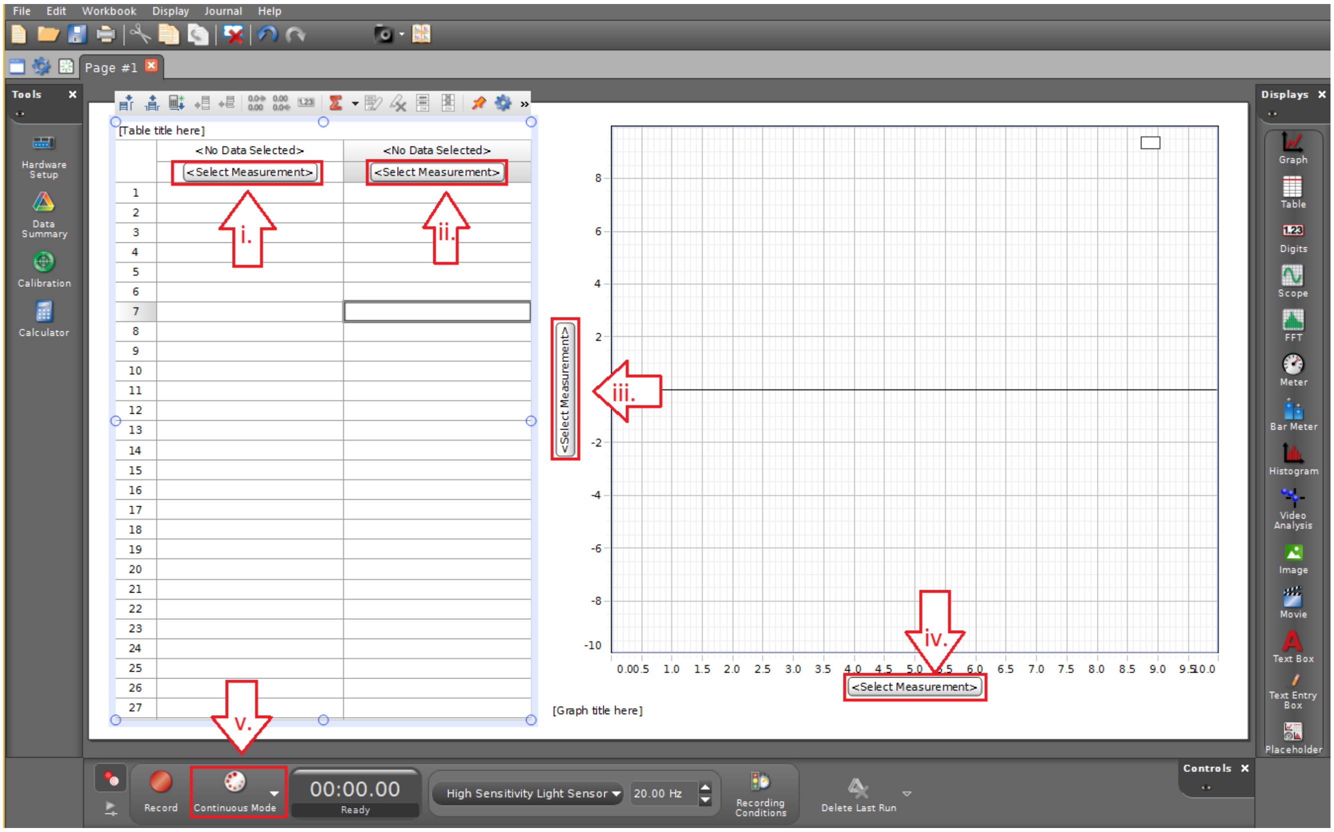
resistivity ($\times 10^{-8}\Omega$-m)	Temperature (K)	resistivity ($\times 10^{-8}\Omega$-m)	Temperature (K)
5.65	300	60.06	2100
8.06	400	63.48	2200
10.56	500	66.91	2300
13.23	600	70.39	2400
16.09	700	73.91	2500
19.00	800	77.49	2600
21.94	900	81.04	2700
24.93	1000	84.70	2800
27.94	1100	88.33	2900
30.98	1200	92.04	3000
34.08	1300	95.76	3100
37.19	1400	99.54	3200
40.36	1500	103.3	3300
43.55	1600	107.2	3400
46.78	1700	111.1	3500
50.05	1800	115.0	3600
53.35	1900	115.0	3600
56.67	2000	115.0	3600

Capstone Data Acquisition and Analysis Software

1. After beginning a new Capstone session, click the first module on the top left of the screen:



2. To setup data collection (see corresponding figures on next page):
    i. Click “select measurement” at the top of the left-hand column. On the drop-down menu, select “relative intensity”
    ii. Click “select measurement” at the top of the right-hand column. On the drop-down menu, select “create new” followed by “user entered data”. You may now input values of angles into this column. If the angles are entered before recording data, you can watch the plot be generated as the left-hand column is populated with intensity values.
    iii. On the left-hand vertical axis of the plot space, click “select measurement” and select “relative intensity” in the drop-down menu.
    iv. On the bottom horizontal axis of the plot space, click “select measurement” and select “user data 1” in the drop-down menu.
    v. Click the “continuous mode” button near the bottom left of the screen. Select “keep mode” in the drop down menu.
3. To collect data (see corresponding figures on next page):
    i. Click the “preview” button near the bottom left of the screen.
    ii. To record a light sensor measurement, click “keep sample”.
4. Data analysis
    i. After completing data collection, click stop in the bottom left portion of the screen
    ii. Select “file” in the top left corner followed by “export data”
    iii. Export the data as either tab delimited or csv in order to perform analysis in excel.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Tools
Hardware Setup
Data Summary
Calibration
Calculator
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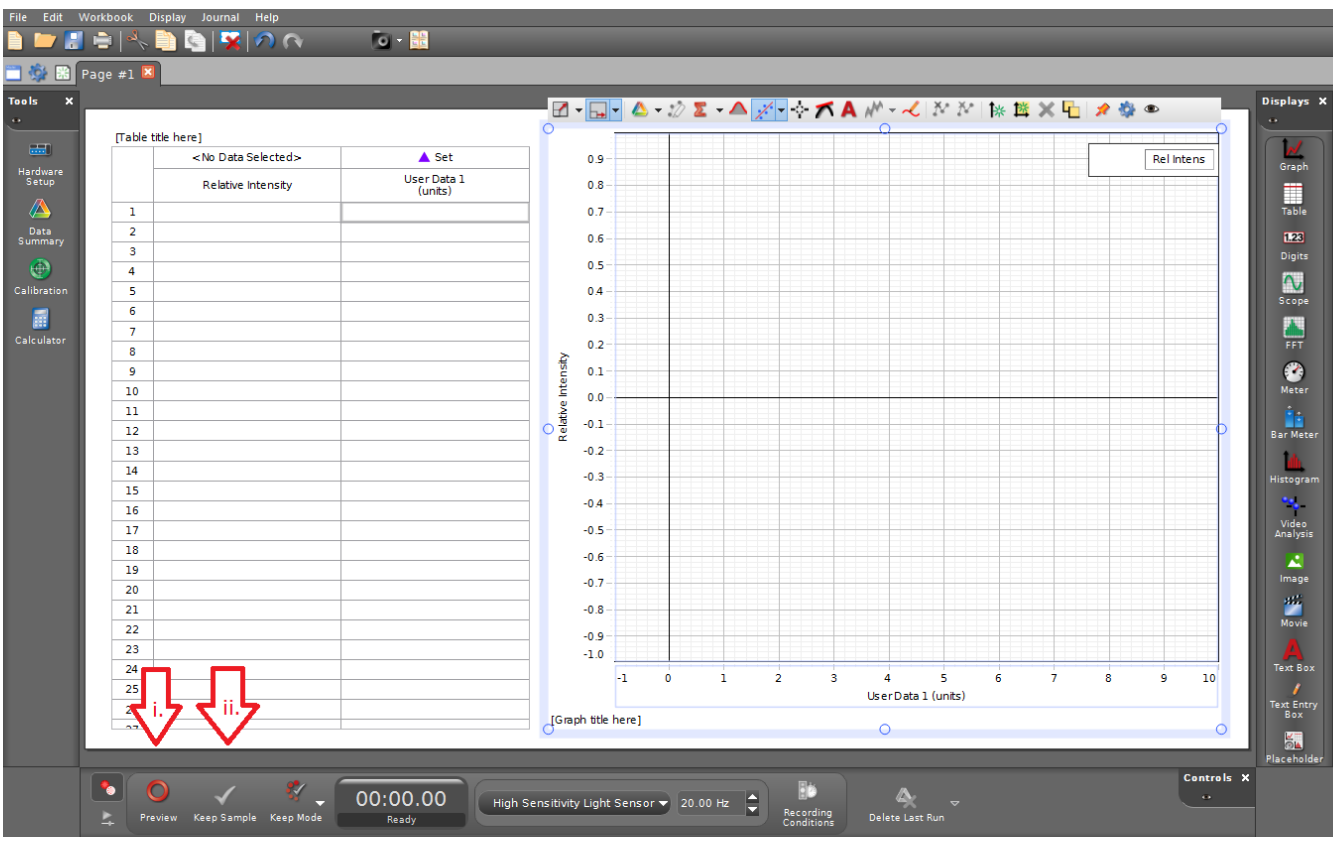
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Tools
Hardware Setup
Data Summary
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Relative Intensity
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User Data 1 (units)
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