PHY143 LAB 3: BLACKBODY RADIATION
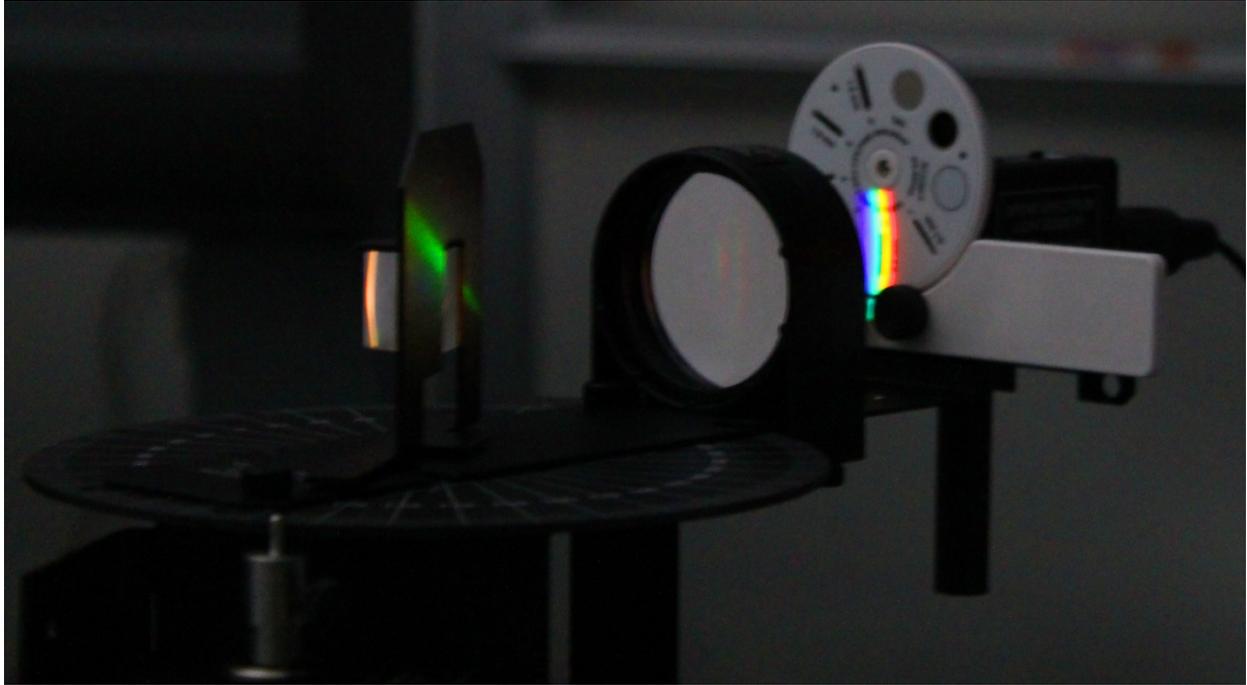
Introduction

A blackbody is defined as an object that perfectly absorbs all (and thus reflects none) of the radiation incident on its surface. When a blackbody is in thermal equilibrium with its surroundings, it must also be a perfect emitter so that the temperature of the blackbody stays the same. But this emitted light is not at the same frequency as the light that was initially absorbed; rather it is distributed between different frequencies in a characteristic pattern called the blackbody spectrum.

The measurement of the blackbody spectrum was the center of a crisis in physics during the early 20th century known as the ultraviolet catastrophe. Different classical models could explain the blackbody spectrum over some frequency ranges, but broke down (in one case predicting infinite radiation at some frequencies). Max Planck eventually resolved the crisis by introducing the quantization of energy, giving birth to the quantum revolution in the process.

In this lab you will use an incandescent light bulb and a prism spectrometer to measure the blackbody spectrum. Although a light bulb is not a blackbody (it emits much more radiation than it absorb!) it is a good approximation of a grey body: an object that emits a fraction of the blackbody spectrum with the same frequency distribution.

Due to this approximation and the simplicity of the apparatus, your intensity data will not quantitatively match that of a blackbody, but the shape of the intensity curve should be qualitatively the same.

Planck's law is derived in the class lectures (see pink notes version). Here we will look at the correspondence between Planck's blackbody function and the Wien and Rayleigh-Jeans functions, which were derived independently. They are good approximations (for short and long wavelengths respectively) of Planck's law for emitted power per unit area per unit solid angle per unit wavelength, which is

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}.$$

We can approximate this function for small (short) wavelengths. When λ is small, $\frac{hc}{\lambda kT}$ is large ($\gg 1$) and thus $e^{\frac{hc}{\lambda kT}} \gg 1$. Thus we can approximate $I(\lambda, t)$ as

$$I(\lambda, T) \cong I_{Wien}(\lambda, T) = \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda kT}}$$

which is the Wien formula, valid only for short wavelengths.

What values of λ can we consider to be sufficiently small, e.g. for $T = 5000K$?

Now we approximate for long wavelengths. When λ is large, $\frac{hc}{\lambda kT}$ is small and thus $e^{\frac{hc}{\lambda kT}}$ is close to 1. Applying a linear approximation to $e^{\frac{hc}{\lambda kT}}$ for $\frac{hc}{\lambda kT}$ about 0, we get

$$e^{\frac{hc}{\lambda kT}} \cong 1 + \frac{hc}{\lambda kT}$$

Putting this in $I(\lambda, t)$ yields

$$I(\lambda, T) \cong \frac{2hc^2}{\lambda^5} \left(\frac{\lambda kT}{hc} \right) = \frac{2ckT}{\lambda^4}$$

which is the Rayleigh-Jeans formula, valid only for long wavelengths.

What values of λ are large enough for this approximation, e.g. for $T = 5000K$?

We can use the Planck function to calculate the wavelength of maximum intensity for a given temperature. We maximize the function by setting its derivative with respect to λ equal to zero, using the product and chain rules:

$$\frac{\partial I(\lambda, T)}{\partial \lambda} = 2hc^2 \left(\frac{1}{\lambda^5} \left(\frac{hc}{\lambda^2 kT} \right) e^{\frac{hc}{\lambda kT}} \left(e^{\frac{hc}{\lambda kT}} - 1 \right)^{-2} - \frac{5}{\lambda^6} \left(e^{\frac{hc}{\lambda kT}} - 1 \right)^{-1} \right) = 0$$

This gives us

$$\frac{hc}{\lambda kT} e^{\frac{hc}{\lambda kT}} = 5\left(e^{\frac{hc}{\lambda kT}} - 1\right)$$

Or, solving numerically,

$$\lambda T \approx 0.2897768 \ cm \ K$$

This relationship between the temperature and wavelength of maximum intensity is known as Wien's displacement law.
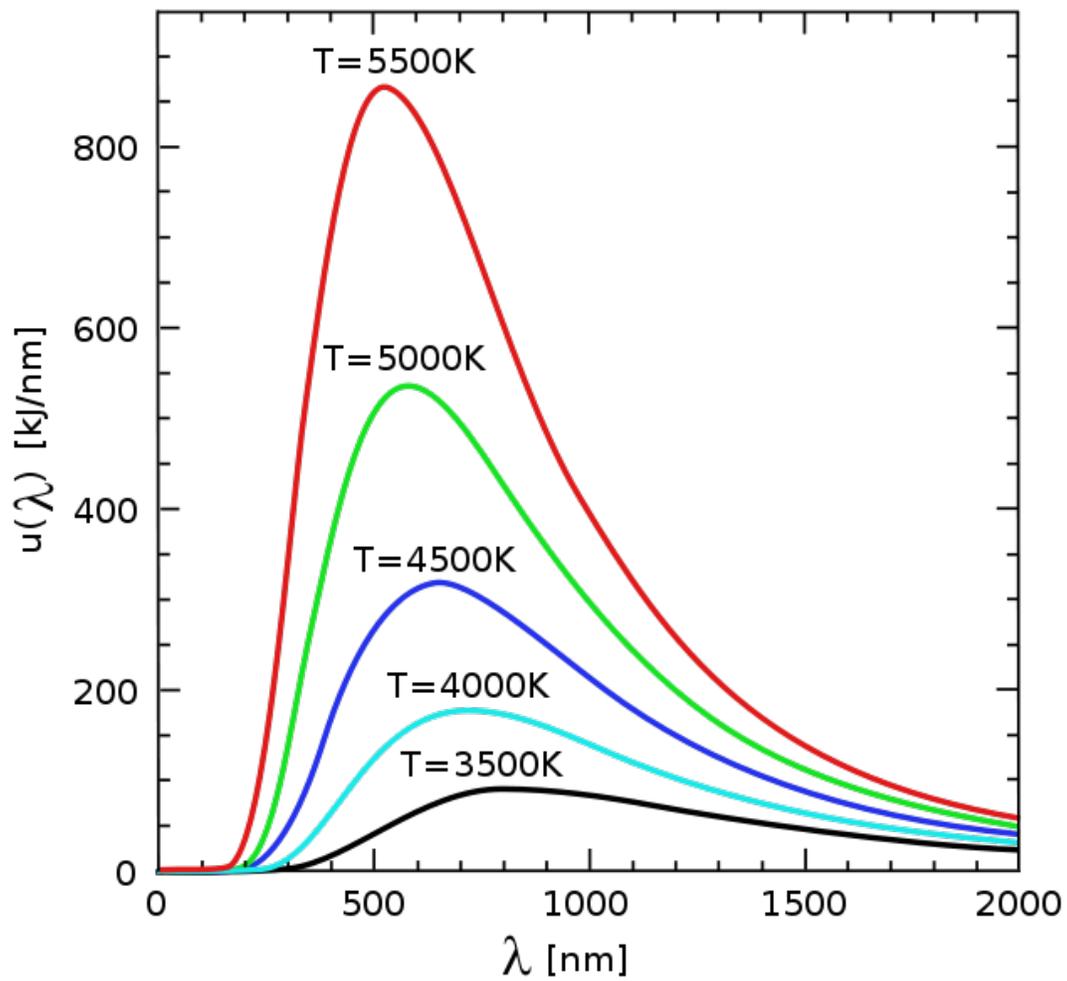
Apparatus Setup

1) Place the Spectrophotometer (Rotary motion sensor + bench + disk) on the optics track.

2) Attach the Broad Spectrum Light Sensor and the aperture plate to the arm of the spectrophotometer using the black rod (image below). Plug the Broad Spectrum Light Sensor into Analog Channel A on the ScienceWorkshop interface.
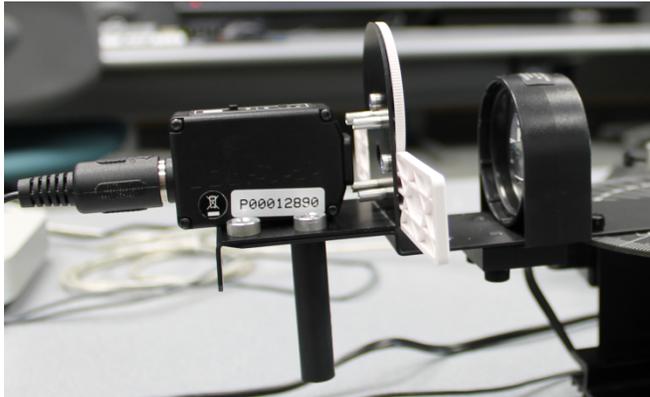
3) Place the focusing lens on the spectrophotometer arm in between the light sensor and the prism, inside of the white angled markings.

4) Plug in the power cable for the power amplifier and connect its cable to Analog Channel C on the ScienceWorkshop interface.

5) Place the incandescent lamp source on the track and connect to the power amplifier outputs with the banana plugs.

6) Attach the Voltage Sensor (banana plugs on one end and analog channel input on the other) to the terminals of the lamp and Analog Channel B. You can plug the banana plugs into the back of the ones coming from the power amplifier. This will allow the computer to measure the voltage across the lamp terminals.
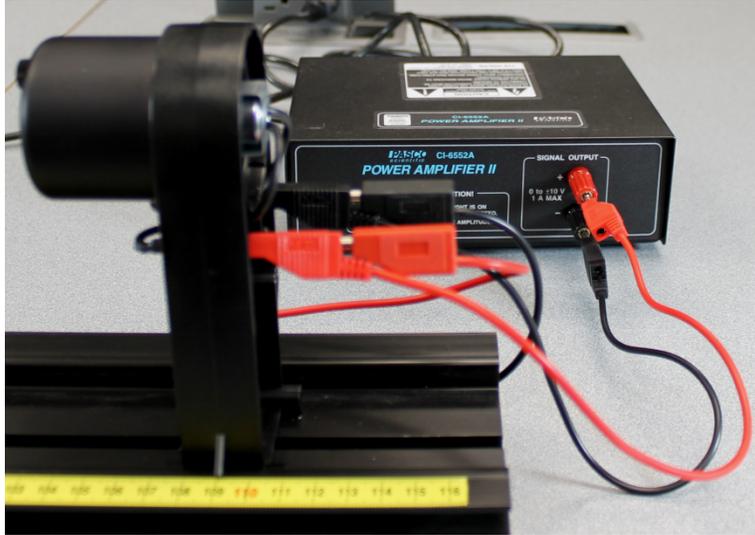
7) Place the collimating slit holder and then the collimating lens in front of the incandescence lamp. Make sure that the collimating lens is about 12 cm from the collimating slits. The lamp should slide into the back of the collimating slit holder. Have someone with 20/20 vision (corrected with glasses is ok) look through the collimating lens at the slits. Adjust the collimating lens until the slits are in sharp focus. The collimating lens should be about 10 cm from the collimating slits.

8) Move the spectrophotometer close to the collimating lens, the focusing lens should now be about 10 cm from the collimating lens.

9) Open the blackbody Capstone file on the computer. On the left side of the screen click Hardware Setup. On the image of the ScienceWorkshop interface click on Analog Channel C. Scroll down the list and click on Power Amplifier. Click Hardware Setup again to close the menu.

10) Click Signal Generator on the left side of the screen. The box next to Amplitude is how you change the voltage. Click On to turn on the incandescent lamp. Turning up the will increase the brightness. Please do not increase the voltage above 7 volts as it drastically decreases the life of the bulb.
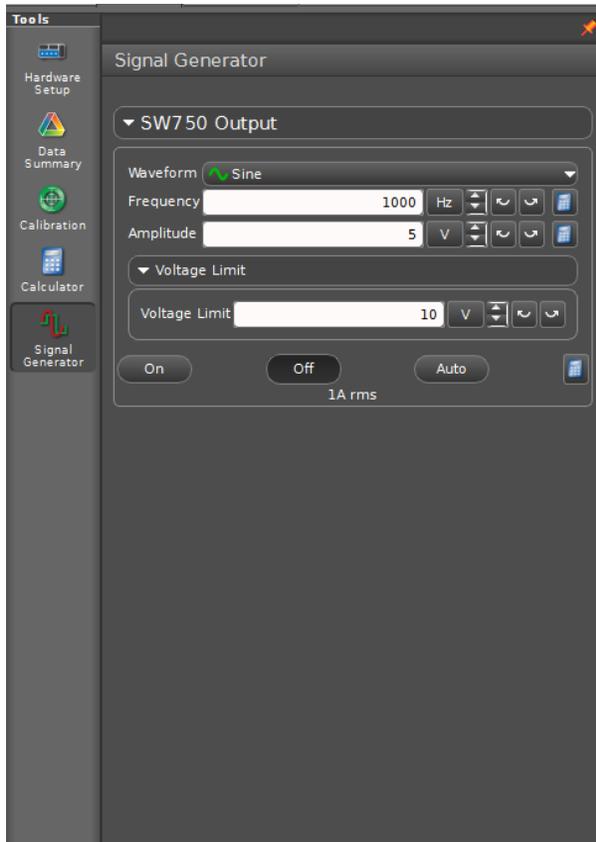
11) Position the Aperture Bracket so that you can see the thin beam of white light. Move the focusing lens so that you get the most in focus beam of light on the Bracket (This should be towards the rear of the angled box).

- How should you chose which slit to use during your experiment? Hint: both the collimating slits and the aperture slits should be the same number. What are the advantages and disadvantages of using a larger collimating slit?
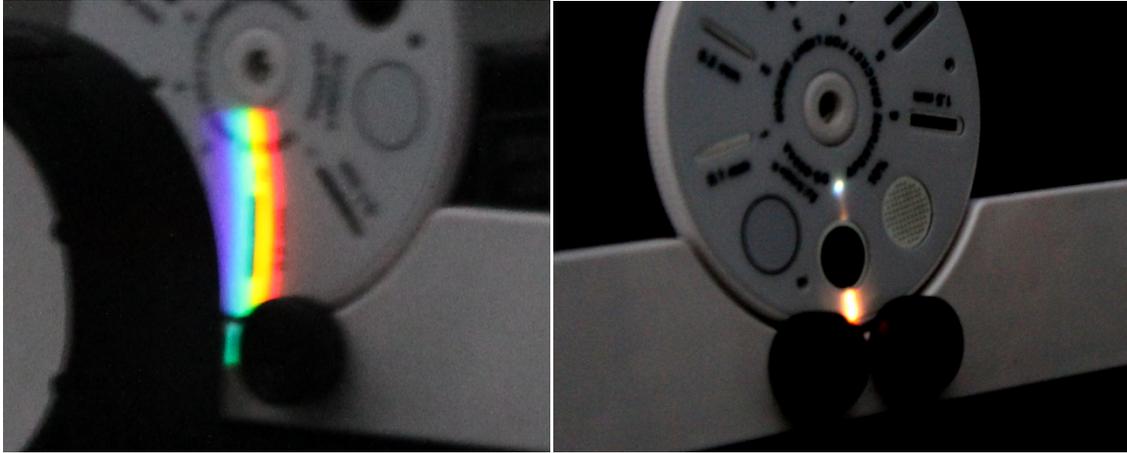
COMPUTER SETUP

1) Open the rotary sensor calibration Capstone file. The purpose of this program is to determine the relationship between the rotation of the spectrometer arm and the rotation recorded by the rotary sensor.

2) Click "Record", then rotate the spectrophotometer arm between two degree marks. If the reading goes negative, reverse the rotary sensor's connection to the ScienceWorkshop interface.

3) Write down the number of radians the rotary motion sensor rotates (shown on the screen) for your given rotation.
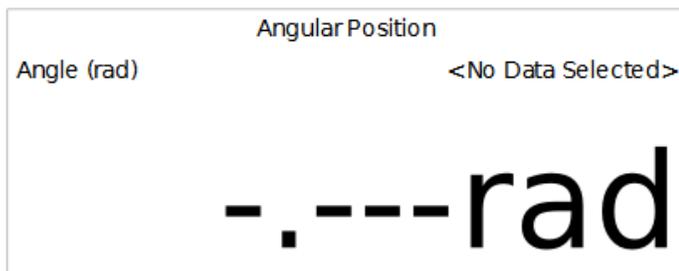
- Should you sweep through a small or large angle to make the procedure more accurate?
- How will ambient light affect your measurements? What are the sources of ambient light around your experiment, and how can you minimize them?

Angular Position

Angle (rad)   <No Data Selected>

-.---rad

4) Take the number of degrees that you rotated the spectrophotometer arm and divide it by the number of radians that you got. The number you should get should be around 0.96.

5) Open the blackbody Capstone file. Click on Calculator found on the left side of the screen. On line 7, replace the number .9569 with the number that you got in the previous step. Click Accept, then click Calculator again.
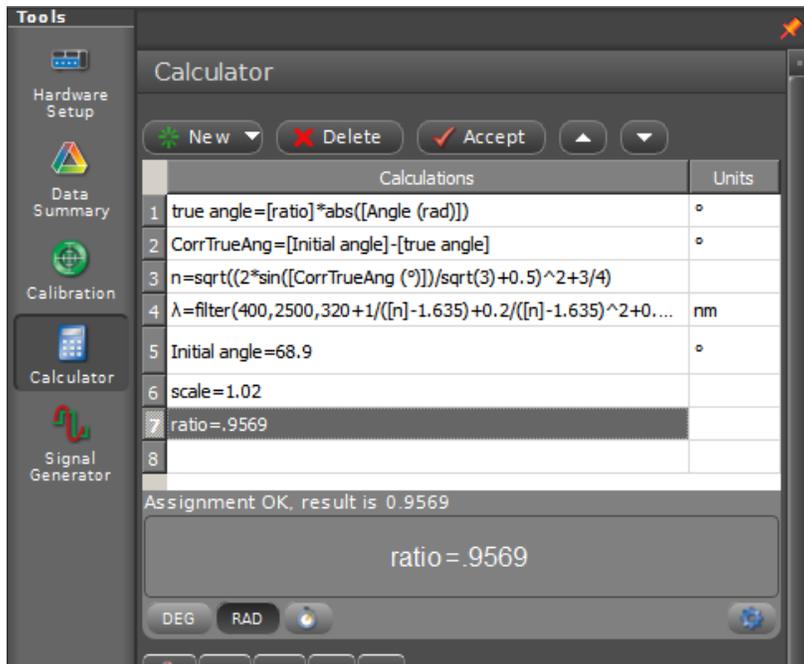
6) Move the sensor arm to its starting position (where it hits the side of the mount, so that you can repeatedly start from the same point).

7) Hit Record. Before moving the sensor arm, hit the TARE button on the sensor. This must be done prior to each run.

8) Slowly move the detector arm around until it passes the bright reference band.

9) On the *Angle Graph* window, find the angle (in radians) of the reference band.
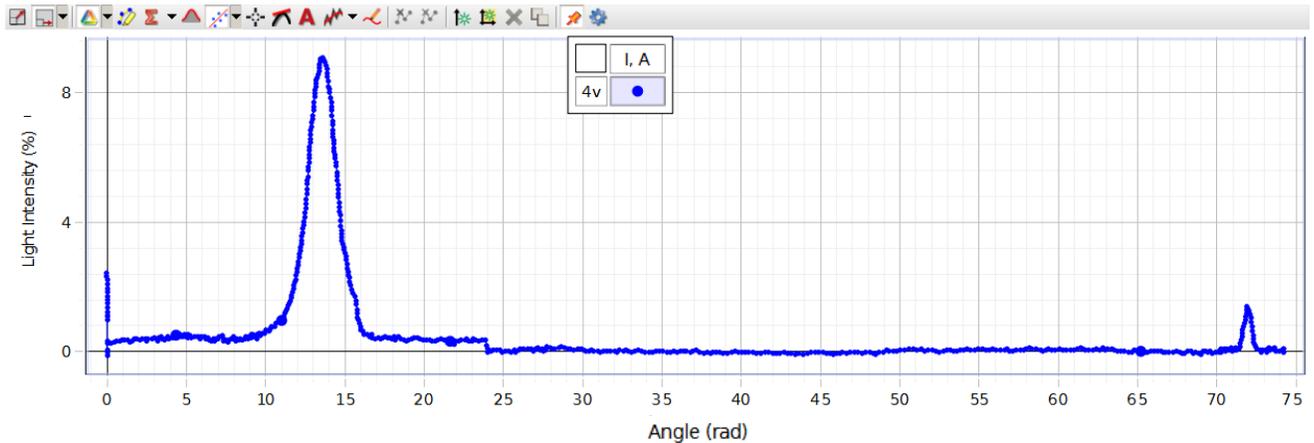
10) Click on Calculator. On line 5 replace 68.9 with the angle you found from the step above. Click on Calculator again to close this menu. This calibration will allow Capstone to calculate and display the intensity as a function of wavelength.
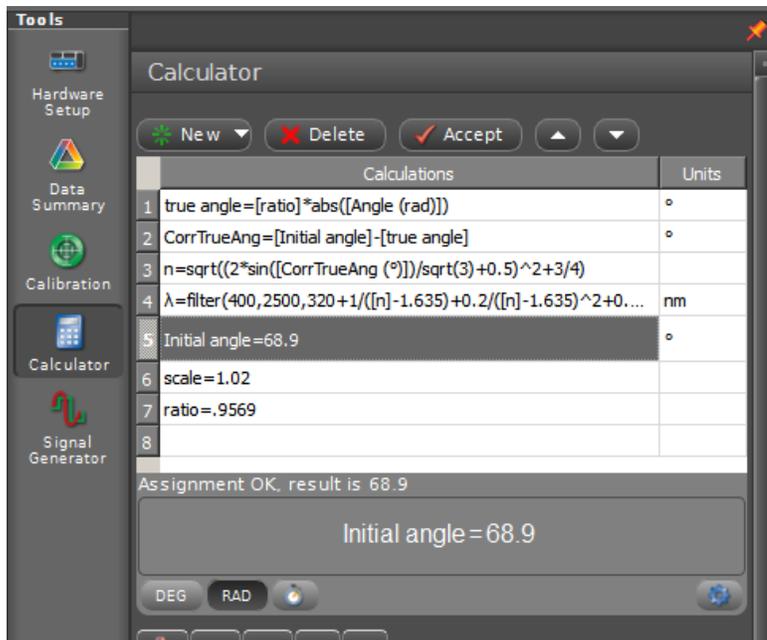
11) Data runs you now take will have correctly calibrated Intensity vs. Wavelength graphs. You may now click on the Blackbody tab to start taking data.
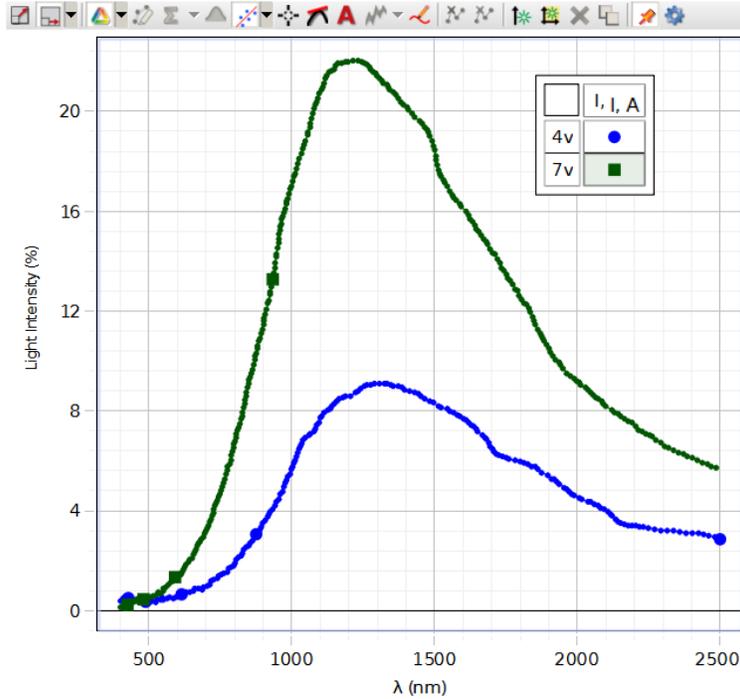
PROCEDURE

Use the spectrometer to record the blackbody spectrum at five different temperatures. The temperature can be set by changing voltage over the light bulb filament. Try to choose temperatures that give noticeably different blackbody curves.

Fit your data in IGOR pro to calculate the approximate temperature of the filament for each measurement. Find the wavelength of peak emission. Does your measurement agree with Wien's Law?