Physics PHYS 275
Experimental Physics Lab

Blackbody Radiation

I. Introduction

You have probably noticed at one time or another what happens to a piece of metal when it is heated to a very high temperature – it begins to glow. First the metal may look a dark black color, but as it heats up it begins to emit light: first a dull red light, then as the temperature is increased, it glows orange, yellow and finally white. As it heats up, you also will notice that it gets brighter, that is, it emits more intense light.

The light that is emitted by an object as it heats up is called blackbody radiation. A perfect black body is an object that absorbs all of the light falling on it. An example of a nearly perfect blackbody would be a small hole in the wall of a cavity. Light enters the cavity, and after several reflections is absorbed. The chance of the light being reflected back out the hole is very small.

Calculations based on classical physics give what is known as the Rayleigh-Jeans equation for the power radiated per unit area per unit wavelength

$$R(\lambda,T)=\frac{2\pi ckT}{\lambda^4} \tag{1}$$

where c is the speed of light, 3×10^8 m/s, *k* is the Boltzmann constant, 1.38×10^{-23} J/K, *T* is the absolute temperature, and λ is the wavelength. This result caused great consternation among the physicists of that time, and was called the “ultraviolet catastrophe”, since the formula predicts that as wavelength is decreased, the power radiated will increase. Thus, every object would be radiating an infinite amount of power in the form of electromagnetic waves, an obviously unphysical result. As is seen in Figure 1, the measured power actually begins to decrease at short wavelengths.

Max Planck, in 1900, realized that this result could be modified by making the assumption that electromagnetic radiation is emitted in discrete packets, or “quanta”, of energy, nowadays called photons.

If each photon has an energy related to the classical frequency by

$$E=hf\ , \tag{2}$$

where *h* is Planck’s constant, 6.626×10^{-34} J·s, then the blackbody spectrum for the power radiated per unit area per unit wavelength becomes

$$R(\lambda,T)=\frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda kT}}-1\right)} \tag{3}$$

which agrees very well with experimentally measured values.

This power distribution has its peak at the wavelength

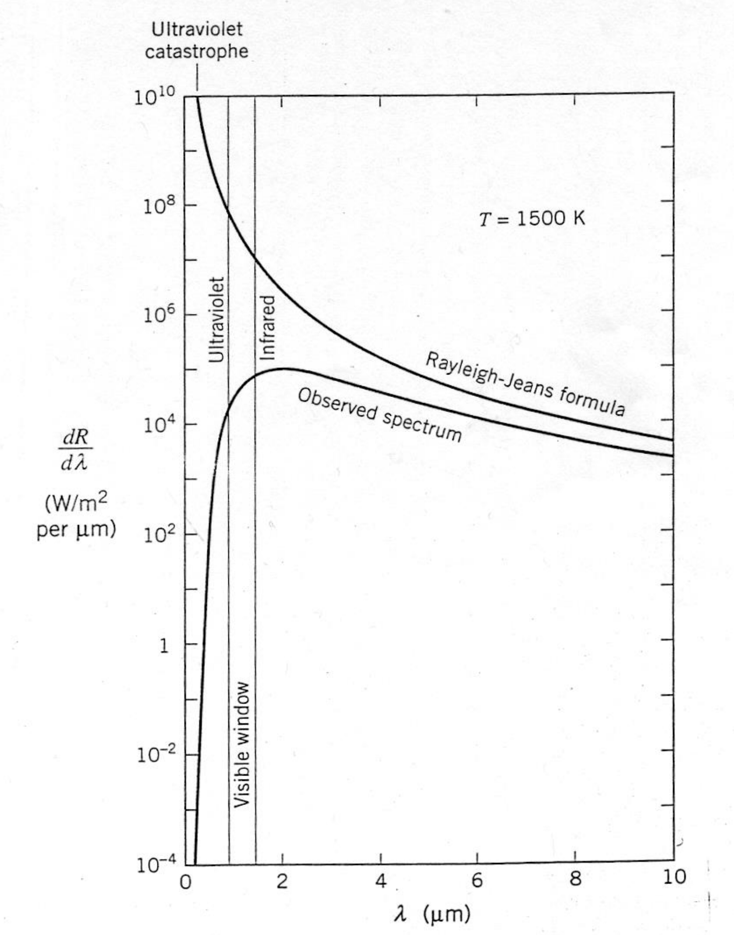

Figure 1– A plot of the power per unit area per unit wavelength predicted by the Rayleigh-Jeans formula, as compared to the measured radiation spectrum for a 1500 K blackbody. (taken from J. Rohlf, **Modern Physics from α to Z^0**, John Wiley and Sons, 1994.)

given by Wien’s Law

$$\lambda = \frac{hc}{(4.965)kT} = \frac{2.9\times10^{-3}\ \mathrm{m\cdot K}}{\mathrm{T}} \tag{4}$$

and predicts that the total power emitted per unit area is given by the Stephan-Boltzmann Law

$$R(T) = \sigma T^4 \tag{5}$$

where $\sigma = 5.67\times10^{=8}$ W/m^2·K^4.

II. Experimental Apparatus

To measure the blackbody spectrum of a hot tungsten filament, the apparatus shown in Figure 2, and Figure 3 will be used. The blackbody light source consists of a bulb with a tungsten filament. As current is passed through the filament it heats up, emitting electrometric radiation with a nearly blackbody spectrum. The radiation, which peaks in the infrared, is collimated by a slit and focused with the collimating lens. It then enters a 60° prism with refracts the different wavelengths into different angles relative to the incident beam. This radiation is then focused onto an infrared or broad spectrum detector by another lens. The detector can be rotated to various angles using a “degree plate” with an attached Vernier rotary motion sensor. The intensity of the incident radiation, as well as the angle, is read into the computer using the Vernier interface.

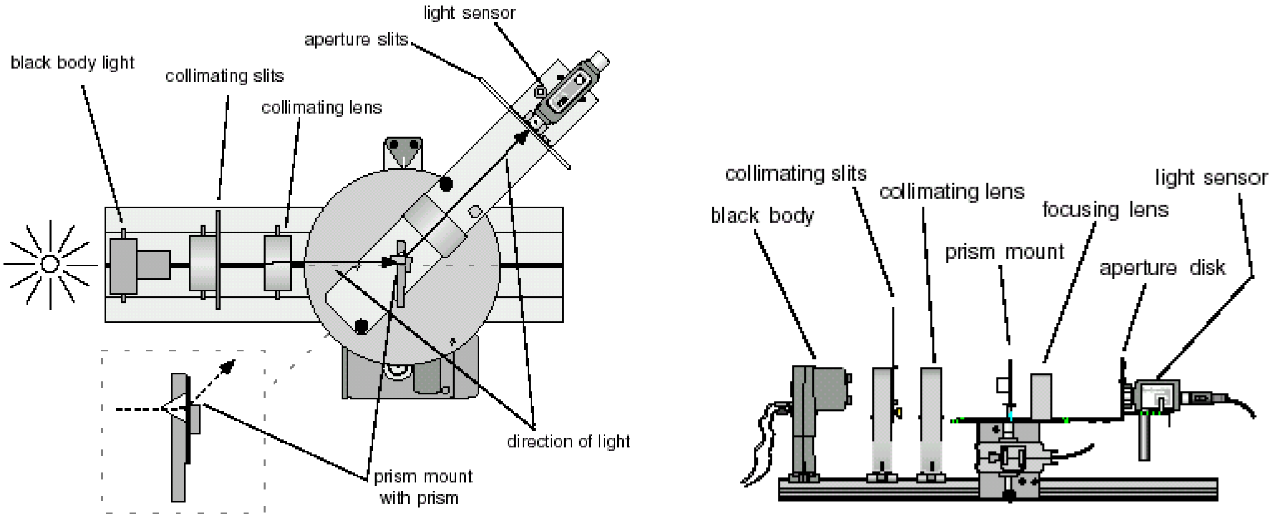

Figure 2 -- The experimental setup for the blackbody spectrum measurement. Light from the blackbody source is collimated, passes through a prism, and is deflected into an infrared sensor.

The infrared detector is a PASCO CI-6628, which includes a high-output, thin film, silicon based device that has 48 thermopile junctions. More information about the sensor can be found in the PASCO CI-6628 manual at ftp://ftp.pasco.com/Support/Documents/english/CI/CI-6628/012-06915b.pdf. The PASCO CI-6630 broad spectrum detector manual can be found at ftp://ftp.pasco.com/Support/Documents/english/CI/CI-6630/012-08541b.pdf. These devices cannot be directly used with the Vernier interface. The output on each pin of these devices is shown in Table 1, and a drawing of the connector in Figure 4.

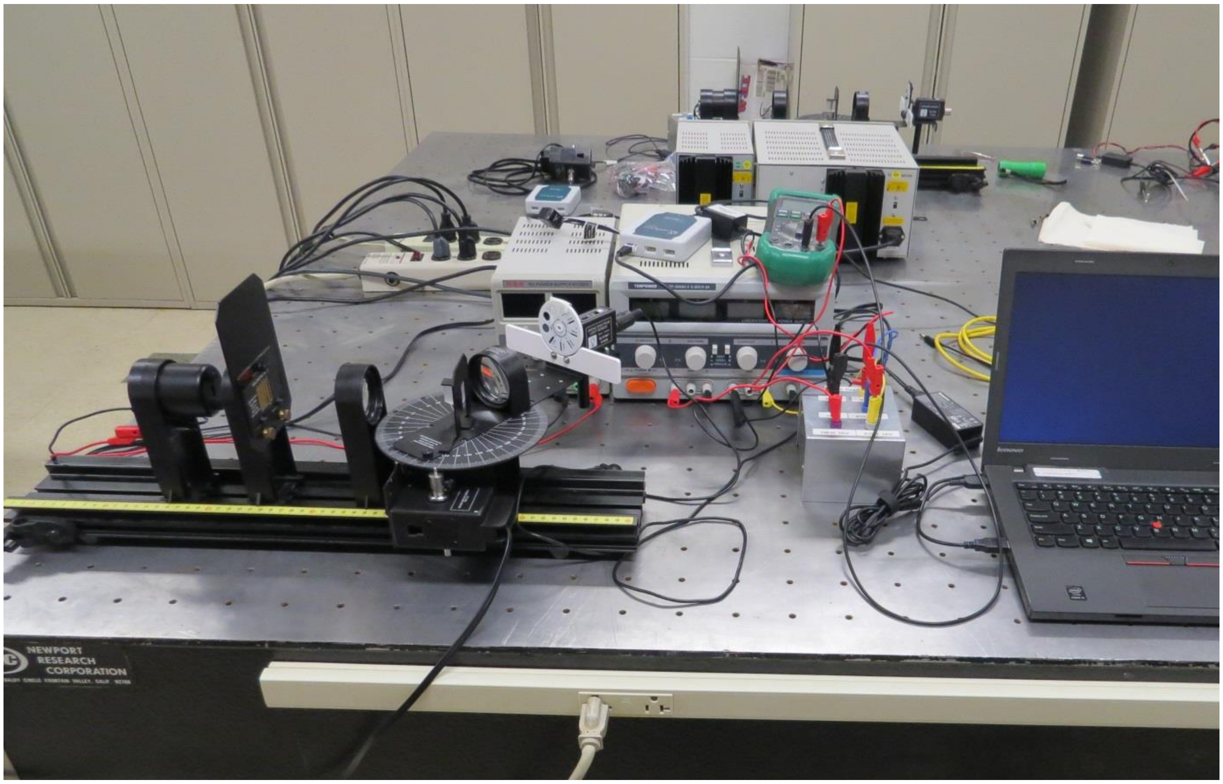

Figure 3 -- A photograph showing the apparatus.

In order to use the IR sensor with the Vernier Lab Quest, a connector box was constructed which allows the correct power supply voltages to be connected to the detector, and allows the sensor output to be read as a voltage directly into the Vernier interface. The Vernier interface only accepts voltages in the range of -10-10 V (using the differential voltage probe), which is acceptable for our application, which usually produces about 0.5 V (on the 10x scale).

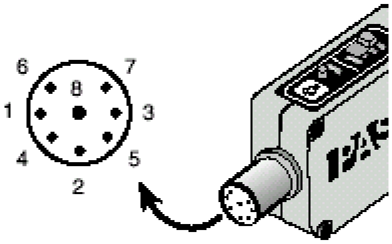

Figure 4 -- A diagram showing the DIN connector pins of the CI-6628 PASCO infrared sensor.

Table 1 – The specifications for the DIN connector on the PASCO-6628. The colors indicated are the internal wire colors of the cable.

Pin	Specifications	Color
1	analog output (+), -10 to +10 V	Black
2	analog output (-), signal ground	Brown
3	(no connection)	
4	+ 5 V DC power	Red
5	power ground	Orange
6	+12 VDC power	Yellow
7	-12 VDC power	Green
8	(no connection)	

III. Experimental Procedure

Here is a rough outline of the procedure to use on this experiment. You will, I am sure, find improvements. As you make the measurements, be sure to identify sources of uncertainty, and consider how the experiment may be modified to reduce them.

1. Attach the IR light sensor to the sensor arm. The manual suggests that you use the infrared filter to shield the sensor from other warm objects in the room, like your hands, etc. I never noticed this problem, and using the filter may affect your results at longer wavelengths. You may wish to investigate this further.
2. Place collimating lens close to but not touching the degree plate.
3. Place the collimating slits exactly 10 cm from the collimating lens.
4. Place the light source as close as possible to the collimating slits.
5. Set the collimating and aperture slit widths. Use the same width on both the collimating and aperture slits. Why? What are the concerns that are relevant to selecting the width? Which width should you use?
6. Turn on the voltage to the blackbody light source. These are 7 V bulbs, so to begin with turn it up to 7 V. We will measure the spectrum with the bulbs all the way to 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.
7. Line up the “white light” that passes under the prism with the aperture slit. This should correspond to zero degrees on the degree plate.
8. Make sure the prism remains fixed when you rotate the table. Make sure the bracket is aligned along the 0-180° line.
9. Calibrate the rotary motion sensor. Record the values returned by the rotary motion sensor in the 0° position and in the position fully rotated (about 170°). Remember, every time you collect data you need to re-zero the rotary motion sensor.
10. With the sensor in the fully rotated position, place an object between the collimating slits and lens, then press “tare”.
11. Return the sensor to the 0° position.

12. Scan a spectrum. First press “collect” in Logger Pro, then slowly move the arm from 0° to the filly rotated position. You will pass the sensor through the visible light band. The most important region of the spectrum is just before this, between about 145° and 160°. You will most likely want to collect about 50 positions/sec, which is the maximum for the rotary motion sensor.

13. Repeat your measurement at a different bulb voltage. Try to span the range 5-10 V in 1 volt increments.

IV. Data Analysis

When you finish collecting your data, you will have several tables containing angles (in rotations of the rotary motion sensor) and IR intensities. To use these, you need to make several computations. You may either use the Logger Pro software itself, or export your data and use Microsoft Excel.

1. The rotations of the rotary motion sensor need to be converted into angles in degrees or radians. To do this, make use of the calibration information you collected. Use the equation for a line, and the value corresponding to the fully rotated angle. If you began your scan at 0°, then the value returned by the rotary motion sensor at 0° will be 0.

2. You will need to determine the wavelength that is incident on the detector when the detector is at a certain angle. The formula, which is reproduced below, is derived carefully on pages 2 and 3 of the manual for the infrared spectrometer, which can be found at ftp://ftp.pasco.com/Support/Documents/english/OS/OS-8542/012-07105B.pdf.
   The wavelength (in nm) is given by

$$\lambda = \sqrt{\frac{A}{n-B}} \tag{6}$$

   where n is the index of refraction for the wavelength λ and is given in terms of the angle θ as

$$n = \sqrt{\left(\frac{2}{\sqrt{3}}\sin\theta + \frac{1}{2}\right)^2 + \frac{3}{4}} \tag{7}$$

   and A and B are experimentally determine coefficients depending on the type of glass. For our prism they are $A = 13{,}900$ and $B = 1.689$.

3. For each blackbody temperature (i.e. filament voltage) make a plot of the voltage output of the infrared detector versus the wavelength for the range of wavelengths between 0 and 8000 nm. On your plots also show the theory curve given by Eq. 3. To do this, you will need to know the temperature. Since you do not know the absolute normalization of your measurements, you will need to normalize your theory curve to one of your data points.

4. Determine the temperature of the blackbody from the voltage and current. This is worked out on page 4 of the blackbody instruction manual at https://d2n0lz049icia2.cloudfront.net/product_document/Black-Body-Light-Source-Basic-Optics-Manual-OS-8542.pdf.
   It is given by

$$T = T_0 + \frac{\frac{R}{R_0} - 1}{\alpha_0} \tag{8}$$

   where R_0 is the resistance of the filament at room temperature T_0, and α_0 is the coefficient of resistance of tungsten (from which the filament is made) which is about 4.5×10^{-3} /K.

5. For each temperature (i.e. filament voltage), determine the wavelength of maximum intensity. Compare the prediction of Wien’s Law (Eq. 4) with your measurements by making a plot showing both.
6. Determine the maximum intensity for each temperature, and compare these values with the prediction of the Stephan-Boltzmann Law, Eq. 5. Do they agree? Is the Stephan-Boltzmann law intended to describe the maximum intensity?

V. Laboratory Report

1. In your laboratory report be sure to include a detailed description of how you made your measurement -- describe the apparatus and the procedure you used to make the measurement.
2. You definitely should include a schematic diagram of the experiment as it actually was (i.e. don't count on it being exactly what is in this lab handout.)
3. You should have plots showing the intensity vs. wavelength for filament voltages of 5, 6, 7, 8, and 9 volts, which include the theory prediction of Eq. 3.
4. You should have a plot comparing the prediction of Wien’s Law to your measurement.
5. You should have a plot comparing the prediction of the Stephan-Boltzmann Law to your measurement.
6. You should you should discuss the uncertainties present in your measurement.