Blackbody Radiation

PHY293, PHY324 - TWO WEIGHTS

PHY294 - ONE WEIGHT

RECOMENDED READINGS
1) R. Harris: Modern Physics, Ch.3, pp. 74-75; Ch.9, pp.384-85. Addison Wesley, 2008.
2) Daniel V. Schroeder: Introduction to Thermal Physics, Ch.7. Addison Wesley Longman Publishing, 2000.
3) PASCO Instruction Manual and Experiment Guide for the Blackbody Radiation at https://www.pasco.com/file_downloads/Downloads_Manuals/Black-Body-Light-Source-Basic-Optics-Manual-OS-8542.pdf
4) Marcello Carla: "Stefan–Boltzmann law for the tungsten filament of a light bulb: Revisiting the experiment". Am. J. Phys. V. 81 (7), 2013. http://studenti.fisica.unifi.it/~carla/varie/Stefan-Boltzmann_law_in_a_light_bulb.pdf

INTRODUCTION

All material objects emit electromagnetic radiation at a temperature above absolute zero. The radiation represents a conversion of a body's thermal energy into electromagnetic energy, and is therefore called *thermal radiation*. Conversely all matter absorbs electromagnetic radiation to some degree.

An object that absorbs all radiation falling on it at all wavelengths is called *a blackbody*.

It is well known that when an object, such as a lump of metal, is heated, it glows; first a dull red, then as it becomes hotter, a brighter red, then bright orange, then a brilliant white. Although the brightness varies from one material to another, the color (strictly spectral distribution) of the glow is essentially universal for all materials, and depends only on the temperature. In the idealized case, this is known as *blackbody,* or *cavity, radiation.* At low temperatures, the wavelengths of thermal radiation are mainly in infrared. As temperature increases, objects begin to glow red. The concept of the blackbody is an idealization, as perfect blackbodies do not exist in nature.

Experimentally, blackbody radiation may be measured as the steady state equilibrium radiation from a cavity in a rigid body. A good approximation of black body absorption is a small hole leading to the inside of a hollow object.

A closed oven of graphite walls at a constant temperature with a small hole on one side produces a good approximation to ideal blackbody radiation emanating from the opening. Blackbody radiation becomes a visible glow of light if the temperature of the object is high enough. At 1000 K, the opening in the graphite oven looks red; at 6000 K, it looks white. No matter how the oven is constructed, or of what material, as long as it is built such that almost all light entering is absorbed, it will be a good approximation to a blackbody, so the spectrum, and therefore


http://mechipediaa.blogspot.ca/2014/05/ablack-body-is-theoretical-object-that.html
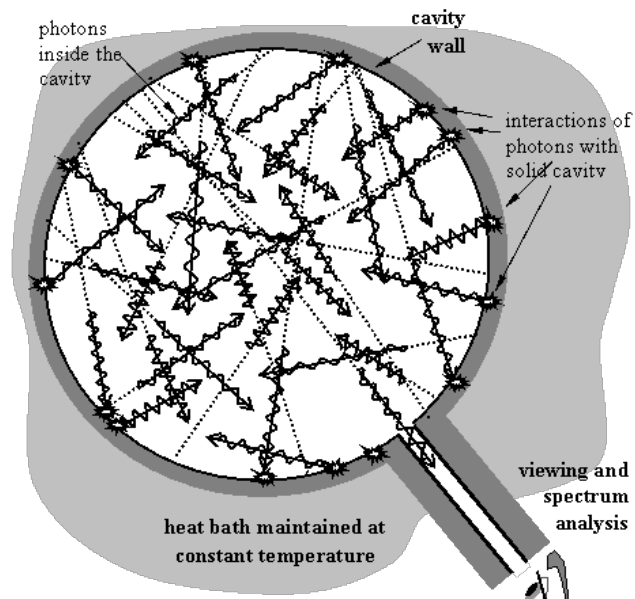
color, of the light that comes out will be a function of the cavity temperature alone.

Classical physics suggested that all modes had an equal chance of being produced, and that the number of modes went up proportional to the square of the frequency. The predicted continual increase in radiated energy with frequency was named "the ultraviolet catastrophe" (Fig.1):
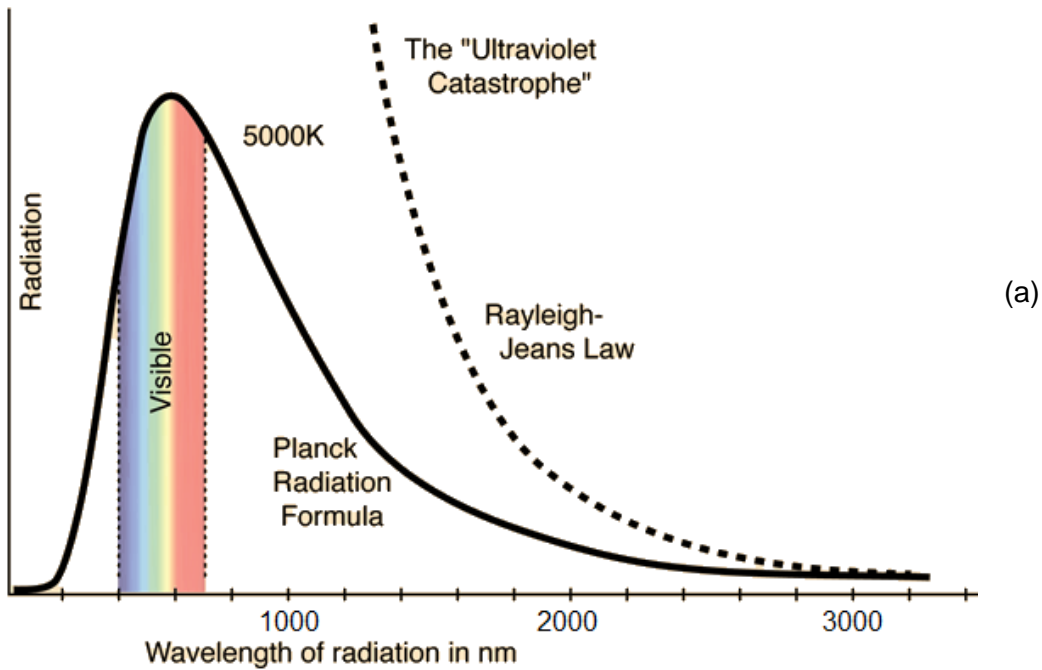
(a)
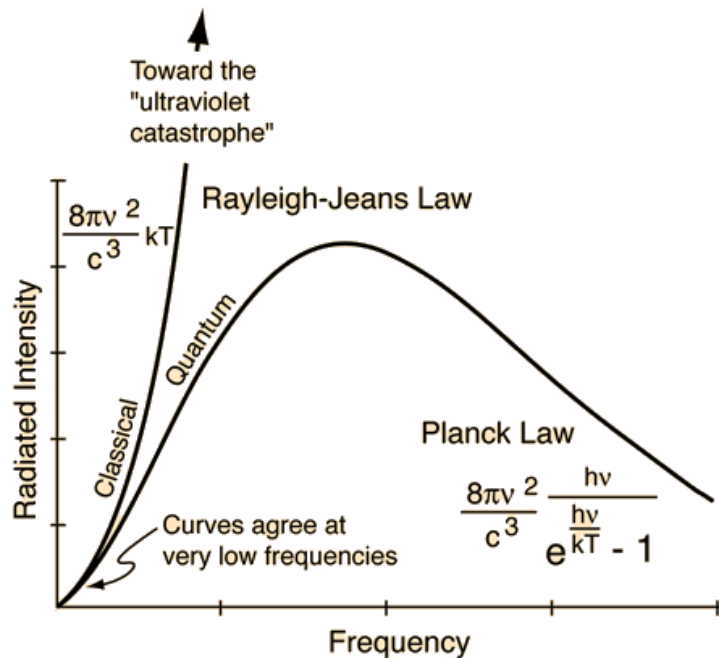
(b)

Fig. 1: The amount of radiation as a function of wavelength (a) and frequency (b) of thermal radiation: classical (Rayleigh-Jeans Law) and quantum (Planck Law) theories/ (http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html).

THEORY

The energy of blackbody radiation varies with temperature and wavelength. As the temperature increases, the peak of the intensity of blackbody radiation shifts to lower wavelengths. This explains why heated objects change appearance from not appearing at all (low temperature, infrared emission) to glowing red (peak in visible at the red end of the spectrum). The shift was found to obey the **Wien's displacement law**:

$$\lambda_{max} T = 2.898 \cdot 10^{-3} \text{m} \cdot \text{K} \tag{1}$$

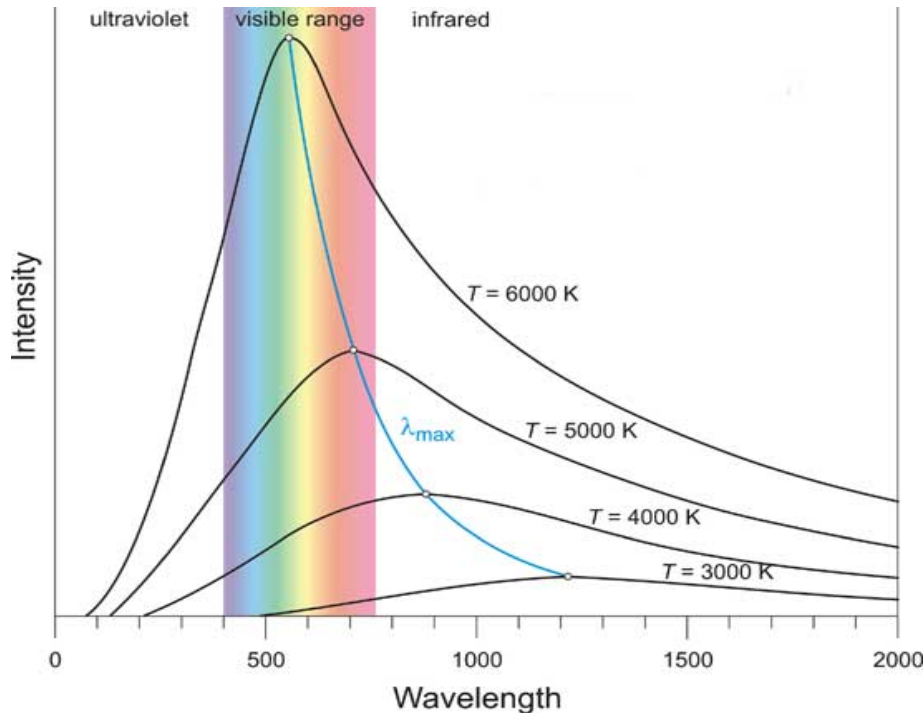where: λ_{max} is the wavelength of the peak and T is the absolute temperature of the emitting object.

Fig.2: Wien's displacement law (from http://www.electrical4u.com/black-body-radiation/).

Another experimental fact is that the amount of energy the heated object emits increases with temperature as in **Stefan-Boltzmann Law**:

$$P/A = I = \varepsilon \cdot \sigma \cdot T^4 \tag{2}$$

where: P is power; A is the surface area of the body; I is the intensity of radiation at the object surface, ε is the emissivity of the surface of the body, and σ is the Stefan-Boltzmann constant, which is listed along with other universal constants in any textbook in Physics. For the majority of objects, $\varepsilon < 1$, and they are called "grey bodies", while $\varepsilon = 1$ for the blackbody.

Blackbody radiation is emitted in the form of a spectrum, where intensity is a function of frequency or wavelength. Intensity emitted in a unit of solid angle in the wavelength interval $d\lambda$ can be conveniently defined as: $I\,(\lambda,\,T)\,d\lambda$. In the classical model of blackbody radiation, the **Rayleigh-Jeans Law** takes into account that cavity atoms are modeled as oscillators emitting electromagnetic waves of all wavelengths:

$$\frac{dI}{d\lambda d\Omega} = I(\lambda, T) = \frac{2\pi c k T}{\lambda^4} \tag{3}$$

where k is Boltzmann's constant and c is the speed of light in free space. However, only at long wavelengths, the Rayleigh-Jean Law is in a good agreement with experimental data (Fig.1a); the intensity approaches infinity as λ approaches zero, which condition is called the "ultraviolet catastrophe".

In 1900 Planck derived a formula for blackbody radiation which is in total agreement with experimental data (Fig. 1). The intensity of radiation emitted by a body is given by **Planck's Radiation Law**:

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \tag{4}$$

where $h = 6.062 \times 10^{-34}$ J·s is the Planck's constant, k is the Boltzmann's constant, and T is the absolute temperature of the body, and λ is the wavelength of the radiation. At long wavelengths, (4) reduces to the Rayleigh-Jean expression (3) and at short wavelengths it predicts an exponential decrease in intensity with decreasing λ.

Planck's main assumption was based on the idea that marked the birth of quantum theory, namely that energy is emitted only in discrete energy values, or *quants*: $E_n = nh\nu = nhc/\lambda$, where n is an integer, h is a constant (later called the Planck's constant), c is the speed of light, ν is the frequency of radiation and λ is the wavelength.

The total intensity radiated within all wavelengths in all direction is given by the **Stefan-Boltzmann Law** (2) by integrating Eq. (4) over the total solid angle and λ from zero to infinity.

Many commonly encountered light sources, including the sun and incandescent light bulbs, are closely modeled as "blackbody" emitters.

EXPERIMENT

The spectrum of an incandescent light bulb is scanned by hand using a prism spectrophotometer that measures relative light intensity as a function of an incident angle. Due to chromatic dispersion of the material of the prism, different wavelengths have different indices of refraction in the prism. 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 shift in the peak wavelength.

Determining wavelengths from angle measurements

The 60 degree prism is mounted so that the back face is perpendicular to the incident light as can be seen in Fig. 3:
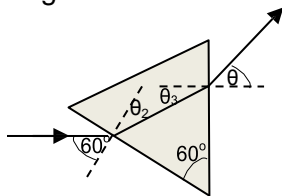

Fig. 3: Schematics of the prism.

Applying Snell's Law at each of the two refracting faces of the prism, we can obtain an expression for the index of refraction of the prism:

$$n = \sqrt{\left(\frac{2}{\sqrt{3}}\sin\theta + \frac{1}{2}\right)^2 + \frac{3}{4}}$$ (5)

The index of refraction varies with wavelength as it can be seen from the table below:

Index of refraction n	Wavelength λ, nm
1.703	1014.00
1.709	852.10
1.717	706.50
1.721	656.30
1.722	643.80
1.728	587.60
1.734	546.10
1.746	486.10
1.748	480.00
1.762	435.80
1.776	404.70

The Cauchy equation gives the relationship between the index of refraction and wavelength:

$$n(\lambda) = \frac{A}{\lambda^2} + B \quad ,$$ (6)

where A and B are constants depending on the prism material. Our prism's coefficients are: A = 13900 nm and B = 1.689.

Derive the final expression for the wavelength: $\lambda = \lambda(\theta)$ combining (5) and (6). Enter the formula into your report and calculate the uncertainty of the wavelength using the propagation of uncertainties formulae.

Determining the temperature of the black body source
The temperature can be estimated indirectly by determining the blackbody electric resistance from the measured voltage and current. The resistance varies with temperature according to:

$$R = R_0[1 + \alpha_0(T - T_0)] \quad , \quad$$ (7)

where α_0 is the temperature coefficient at the room temperature T_0. Our blackbody is the tungsten filament of a light bulb, which has the thermal coefficient $\alpha_0 = 4.5\times10^{-3}$ K^{-1} at $t^o = 20°C$, and R_0 = 1.1 Ω. Solving (7) for temperature, one can obtain:

$$T = T_0 + \frac{\frac{V/I}{R_0} - 1}{\alpha_0}$$ (8)

Voltage (V) and current (I) are displayed by the acquisition software. If the room temperature is significantly different from 20°C (by more than 5%), make a search on the web to find the temperature coefficient of tungsten for the real room temperature and substitute the real temperature in the Eq.(8).

Apparatus

The Prism Spectrophotometer is set up for you. Check that the prism is oriented with the apex facing the light source (Fig. 4). Verify that the base piece of the prism is aligned with the zero mark on the spectrophotometer table when the prism apex points toward the light source.
The collimating lens must be ~10 cm from the collimating slits.
Set the collimating slits on Slit #4. Set the light sensor mask on Slit #3.

Fig. 4.

Acquisition Software

Open the Blackbody Radiation LabVIEW application using the desktop shortcut. Do not turn the acquisition ON yet!
Turn on the Signal Generator (a switch is at the back).

Several buttons are placed at the top of the acquisition window: Clear Data erases the current file; Export Data allows you to save the data (not the plot) as a .txt format; Clean Up Data applies a filter to reduce noise; Integrate Area Under Curve does what it says between two cursor positions set up by the user; Automatic Data Limit Switch allows you to scan the emitted spectrum over 30 degrees or 80 degrees (the initial angle θ_{init} is between 74 and 79 degrees depending on the prism position).

At the bottom, there are display windows for average Voltage and Current as well as for the two pairs of cursors.

Caution: If 10 volts is applied to the blackbody light source for an extended amount of time, the life of the bulb will be reduced. Only turn the bulb on when taking measurements.

PROCEDURE

Note: The light detector has a systematic drift in the output. In order to minimize it, do not bring your hands close to it (you emit infrared radiation, too!), do not touch it and use only the sides of the light sensor mask to move it during the scan.

Rotate the scanning arm counterclockwise until it touches the stop. This will be the starting position for all the scans.

Set the Broad Spectrum Light Sensor gain switch to "x10" and press the tare button. Choose an 80-degree acquisition and select voltage at 6 V.

Look at the light coming from the Blackbody Light Source. Observe and record the color.

Question 1. Are all the colors from red to violet present in the spectrum on the Light Sensor screen?

Slowly rotate the scanning arm through the spectrum and continue all the way until it turns off by itself. There will be a main peak on the intensity vs. angle diagram and also a smaller blip where the light sensor is aligned with the light source because some light passes by the prism instead of going through the prism. This blip enables the *initial angle* θ_{init} to be exactly determined. Due to small displacements of the prism, this angle can slightly alter from experiment to experiment. You should experimentally determine the current initial angle θ_{init} for your device performing 3 - 5 runs to find the position of the small blip, described above.

Record the value of θ_{init} with its uncertainty; its accuracy will greatly affect your result!

Switch to the 30-degree scan; bring the arm back to the starting position.

Exercise 1. Wien's Displacement Law
Using voltages between 10 V and 4 V, take data of voltage and current, and determine the angle of the main peak θ_{peak} by using the cursors on a 30-degree scan. You may need to switch the gain to 100 at lower voltages. After each gain change you have to press the "Tare" button on the light sensor several times.

- To calculate a wavelength, assume that $\theta = \theta_{init} - \theta_{peak}$ and substitute θ into Eq (5). Use the obtained index of refraction in Eq. (6) to find the experimental peak wavelength λ_{exp}.
- Calculate temperature values T using voltage, current and expression (8).
- Use data from Wien's Law and calculate the average value of $T \times \lambda_{exp}$.

<u>**Question 2.**</u> Compare the result with the Wien's displacement constant given by Eq. (1). Discuss the difference.

Exercise 2. Stefan-Boltzmann Law
The light sensor records the relative intensity and returns a voltage value directly related to power per unit area that falls upon it. Make measurements for not less than 7 different values of voltage in the range between 10 V and 4 V. The greater number of runs will increase quality of the result.

For each of the voltage runs from 10 V to 4 V, use vertical cursors to limit the peak area to integrate between 10 and 26 degrees (you may choose other values, if you wish) and use the Integrate button to obtain the area under the curve. Notice that the intensity does not fall to the baseline after the peak due to ambient light. Delimit the "tail" using cursors and re-integrate.

Use the "tail" area value as correction to the peak area value. You also need to calculate the temperatures or use the values calculated before for Wien's Law.

Note: Keep the gain constant from one voltage run to another in this part of the experiment!
- Use data from Stefan-Boltzmann Law and plot: Area vs. T^4.

<u>**Question 3.**</u> How well does your (qualitative) graph compare with Eq. (2)? Analyze the graph in detail. Discuss the effect of the systematic uncertainty and its origin.

ANALYSIS

<u>**Question 4.**</u> How did the color of the bulb change with temperature?

<u>**Question 5.**</u> How did the color composition of the spectrum change with temperature?

<u>**Question 6.**</u> Considering the peak wavelengths, why is the bulb's filament red at low temperatures and white at high temperatures?

<u>**Question 7.**</u> For the highest temperature, is more of the intensity (the area of the intensity vs. wavelength graph) in the visible part of the spectrum or in the infrared part of the spectrum?

<u>**Question 8.**</u> How could a light bulb be made more efficient so it puts out more light in the visible?

Submit answers to all questions from pp. 6 - 7.

This guide sheet was written by Ruxandra M. Serbanescu (v.2 2013).
Larry Avramidis built the Data Acquisition Device and wrote the Labview acquisition program.

Significantly updated in January and September 2017 by Natalia Krasnopolskaia.