Calculating Wien's Constant and Evaluating the Accuracy of a Simulation

Candidate number:
IB Physics HL
Session:

Design

Background Information:

Derived from Planck's radiation formula, Wien's displacement law describes the variation of peak emission wavelength with temperature of a blackbody. As implied by the name, a perfect blackbody is black and absorbs all light, rather than reflecting it (Mutlaq, 2013). Due to the lack of reflection, blackbodies heat up more easily than say, objects that are white, and as result release that heat energy through thermal radiation. In the natural universe, perfect blackbodies do not exist, and most objects emit thermal radiation anyway. However, there are many objects, such as stars, that approximate blackbodies (Nave, 2014), so Wien's displacement law permits the calculation of stars' surface temperatures based upon their color. The phenomenon of color is due to various wavelengths of light being emitted, so based on a stars color, it is possible to determine the wavelength of light it is emitting.

Wien's displacement law is:

$$\lambda_{peak} = \frac{2.898 * 10^{-3} m * K}{T}$$

where λ_{peak} is the peak emission wavelength in meters and T is the temperature in Kelvin.

Research Aim:

The goal of this investigation is to calculate Wien's displacement constant from data collected from a computer simulation. I want to compare the constant I obtain to the actual constant in order to analyze the correctness of the simulation used and any improvements that could be made. There are many physics simulations out on the internet, but without knowledge in physics, the validity of these simulations cannot be verified; in other words, the simulation could be using completely incorrect mathematics to model the phenomenon. Additionally, I would like to investigate how computer simulations work in general, as my future career will similarly involve modeling systems. My ultimate aim in this investigation is to see how accurate a computer simulation is compared to reality in terms of Wien's law.

Hypothesis:

Within the simulation, as the temperature (K) increases, the peak emission wavelength (μm) will decrease according to $\lambda_{peak} = \frac{2898 * \mu m * K}{T}$. This is the known law relating wavelength and temperature in blackbodies, so this should be the relationship if the simulation is accurate.

Variables:

The independent variable is the temperature in Kelvin. It is manipulated in increments of 500 K, from 1000 K to 6000 K, thus providing control for this variable.

The dependent variable is the wavelength in micrometers. This variable was not controlled.

In addition to the temperature, another controlled variable in this investigation was the simulation itself. I used the PhET blackbody spectrum simulation for this investigation. Using the same simulation throughout the process provided control as the data collected was calculated from the same simulation mathematics. I chose this simulation specifically because the measurements of peak emission wavelength were not analog; in other words, I had to estimate myself based on the shape of the graph where the peak intensity was and its corresponding wavelength. An analog simulation would not have allowed me to calculate uncertainties in the investigation.

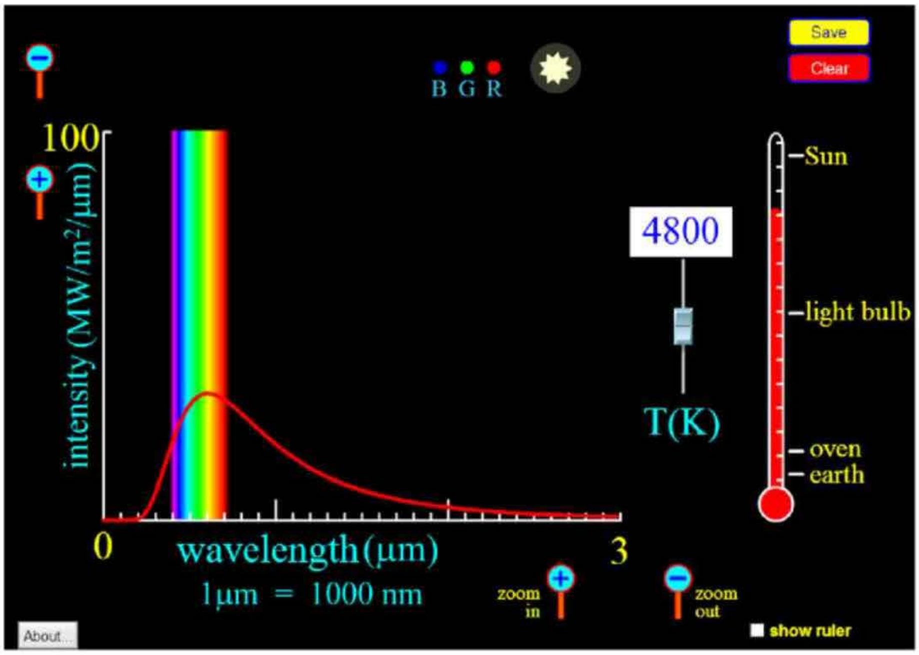
There were no other variables to be controlled in this investigation as it utilized a simulation, which can be isolated from other real world influences. The simulation itself was held constant though; I did not use different simulations throughout the investigation.

Materials:

- Computer
- PhET Blackbody Spectrum simulation
- Spreadsheet/graphing software (such as Microsoft Excel)

Procedure:

1. Go to https://phet.colorado.edu/en/simulation/legacy/blackbody-spectrum and start the simulation. When opened, it should look like this:



2. Click in the box next to "show ruler". A ruler should appear on the screen.

3. In the box above the slider and text saying T(K), type in the first temperature of 6000 K.

4. Approximate the highest point on the red line in the graph. This is its peak intensity. Line up the edge of the ruler with the peak and x-axis.

5. The corresponding intersection on the x-axis is the peak emission wavelength in µm. Record this value.

6. Repeat steps 3-5, decreasing the temperature by 500 K every time until reaching 1000 K. This yields 11 data points. Note: as the temperature decreases, it may be necessary to use the zoom in function on the x-axis within the simulation in order to more accurately approximate the peak.

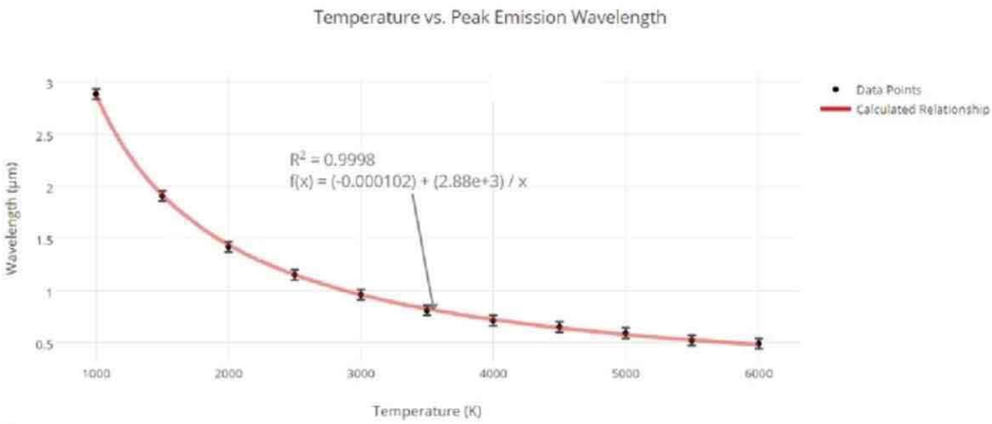
Data Collection and Processing

Raw Data:

Table 1: Temperature and Wavelength

Temperature (K)	Peak wavelength (µm) $\Delta\lambda = \pm 0.05$ µm	T x Wavelength (µm x K)
6000	0.49	2940
5500	0.52	2860
5000	0.59	2950
4500	0.65	2925
4000	0.71	2840
3500	0.81	2835
3000	0.96	2880
2500	1.15	2875
2000	1.42	2840
1500	1.91	2865
1000	2.89	2890

Graph 1: Temperature vs. Peak Emission Wavelength



<u>Processing:</u>

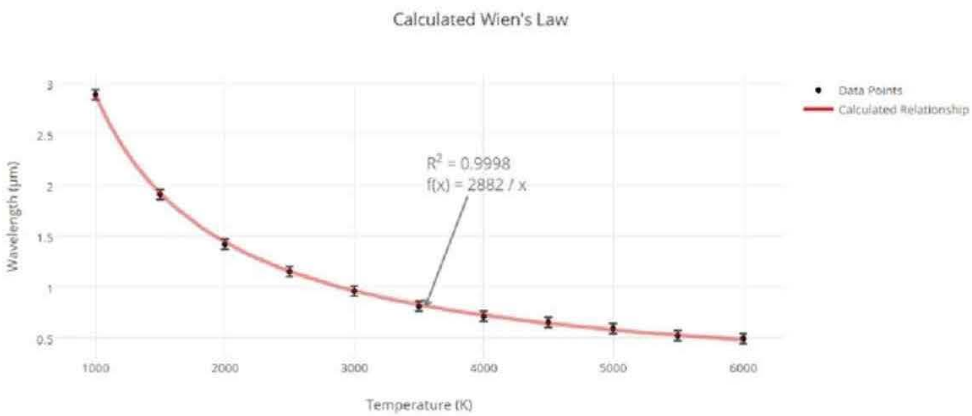
Wien's constant calculation:

Mean of (temperature x wavelength) =

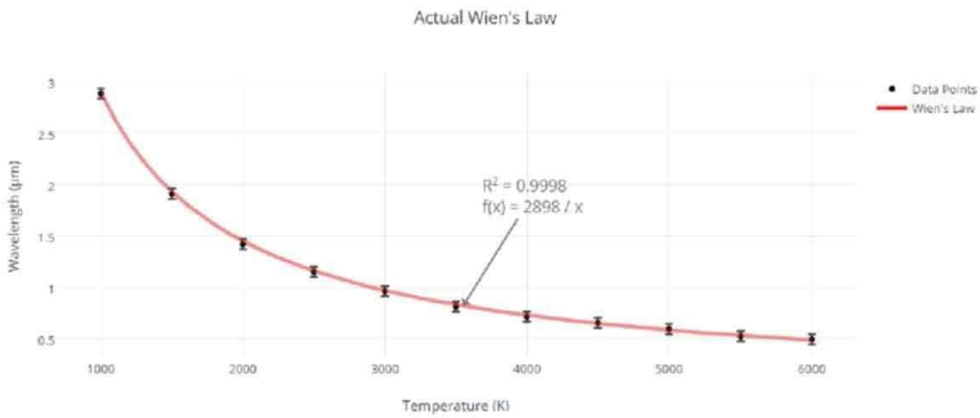
(2940+2860+2950+2925+2840+2835+2880+2875+2840+2865+2890)/11 = **2882 μm x K**

Percent Error = (2898 – 2882)/2898 x 100 = **0.55 %**

Graph 2: Calculated Wien's Law



Graph 3: Actual Wien's Law

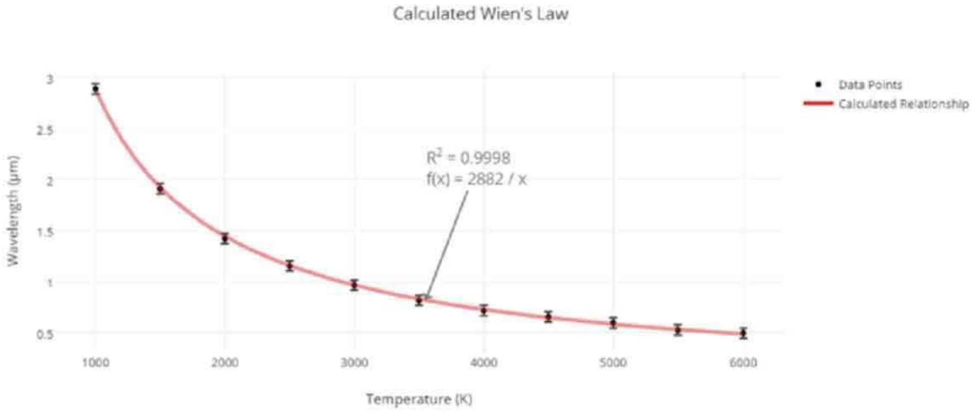


<u>Results:</u>

Table 2: Calculation of Wien's Constant

T x Wavelength (µm x K) ± 600 µm x K	Mean (µm x K)	Wien's Constant (µm x K)	Percent Error (%)
2940	2882	2898	0.55
2860			
2950			
2925			
2840			
2835			
2880			
2875			
2840			
2865			
2890			

Graph 2: Calculated Wien's Law



Conclusion and Evaluation:

Concluding:

The data collected supports the hypothesis that within the simulation, as the temperature (K) increases, the peak emission wavelength (μm) will decrease approximately according to $\lambda_{peak} = \frac{2898 * \mu m * K}{T}$. The calculated Wien's constant was 2882 μm x K (Table 2), slightly less than the actual constant of 2898 μm x K. However, this difference is insignificant as the percent error is only 0.55% (Table 2).

Noting Graph 2 of the observed relationship between temperature and wavelength, as the temperature (K) increased, the peak emission wavelength did in fact decrease. However, it decreased according to $\lambda_{peak} = \frac{2882 * \mu m * K}{T}$ rather than exactly by Wien's Displacement Law. This result still supports the original hypothesis because the difference is rather small between the respective relationships, as mentioned previously with a percent error of 0.55%. Moreover, this percent error is likely due to the uncertainty in the measurement of the peak emission wavelength. The exact location of the peak intensity had to be approximated based on the graph's visual rather than an equation, and as such its corresponding wavelength could have been different by ±0.05 μm. This could have lead to a difference of ± 600 μm x K in the calculated Wien's Constant, which would explain why my result is slightly different than the actual constant. Based upon these results, I would judge the simulation to be accurate, as the data it yields nearly mirrors Wien's Displacement Law.

<u>Evaluating:</u>

There was some error in this investigation, mostly due to the design of the simulation.

1. In the simulation, the x-axis only had increments of 0.1 μm, but obviously the measurements never fell exactly at one of these increments. Rather, I had to estimate, for example, whether the wavelength was .45 or .47 μm, which lead to some inaccuracy. This resulted in a random error of ±0.05 μm.
2. Another source of error was my estimation of the peak intensity. Finding the peak of the curve was based upon my judgement rather than an apparatus actually telling me it was the peak. As such, I may have misjudged the where the peak intensity was, affecting the data for peak emission wavelength.
3. The final issue with this investigation is that I did not fully fulfill my research aim, which was to evaluate the accuracy of simulations. I only evaluated one simulation, and this was due to a time constraint.

Improvements:

To improve my investigation, and find out more about the accuracy of simulations, I would:

1. Create a scale for the x-axis that has more increments. I could do this by simply holding up an actual ruler to the screen and converting the number to its wavelength (μm). This would yield more accurate data for wavelength, as the uncertainty would be much lower.
2. Use an equation to find the value of the peak intensity. This way, I would not just be relying on the graph. The number from the equation would ideally provide me with the correct peak intensity. This would also allow me to see whether the simulation's graph is correct.
3. Allow more time for the investigation and use a variety of simulations. This way I could compare the data from each, and then rate the simulations on their relative accuracy.

References:

Mutlaq, J. (2013, November). Blackbody radiation. Retrieved December 16, 2015, from https://docs.kde.org/trunk5/en/kdeedu/kstars/ai-blackbody.html

Nave, R. (2014). Wien's displacement law. Retrieved December 16, 2015, from http://hyperphysics.phy-astr.gsu.edu/hbase/wien.html#c2