# How Hot Are Stars and Planets?

Tools used in this lab:

* PhET Blackbody Spectrum Simulation

<https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html>

* UNL Astronomy Simulation: Blackbody Curves (NAAP) should already have; installed with the Kepler’s Laws simulation
* Microsoft Excel

## Course Outcomes Met

1. Communicate scientific issues effectively in oral and written form;
2. Distinguish scientific studies from popular opinions by employing critical thinking skills and the scientific method;
3. Effectively collect, analyze and present data and correctly construct and interpret charts, graphs and tables to draw scientific conclusions;
4. Apply the fundamental concepts and methodologies of physics and/or chemistry to investigate a scientific theme.

**Strategy**

Use experimental data to deduce the general laws governing thermal emission of light. Then apply those laws to stars and other systems that emit light due to having a temperature. Since we do not have the equipment to do actual experiments, we will use simulated experiments.

Pay attention to units. Mostly, we will do wavelength in nanometers and temperature in Kelvin but not always.

## A Note on How to Do This Activity

You can certainly just search Google for a lot of this, but that will get you in trouble as you need to give a reason for your answers that follows from earlier questions. Think of this as an example of doing a scientific investigation, starting from some general observations, abstracting physical principles from them, and drilling down to the specific application of those principles to stars.

## The Electromagnetic Spectrum of Light

Nearly everything we know about the universe, we have discovered through looking at the light from celestial objects reaching Earth. Without the ability to investigate these objects directly, the light from them that reaches Earth offers our window into understanding everything from their brightness, size, composition, rotational properties, temperatures, densities, and magnetic field to the expansion of the universe itself. In order to extract this information from just the light, it is necessary that we understand the nature of light itself. It is knowing the properties of light that allows us to learn as much as we do about our universe.

When astronomers refer to light, they are not only referring to the light we observe in our daily lives. They are also referring to types of light invisible to the human eye. The light humans can see is referred to as visible (or optical) light. Some forms of life can see beyond this range and see infrared light or ultraviolet light. You are probably familiar with both of these kinds of light. Infrared (IR) light, in human terms, can be thought of as light from heat. It is the energy that you feel as hot when you get near a hot object. However, all forms of light can be emitted due to heat, not just IR. Ultraviolet (UV) light is why we wear sunscreen during the summer as it is the light that gives you a sunburn. There are other kinds of light as well, and you have likely heard of most of them, but maybe not realized they are light. The seven kinds of light are radio wave, microwave, infrared, visible, ultraviolet, X- ray, and gamma ray light. Taken together, we call this the ***electromagnetic spectrum*** (EM; Fig. 1). More formally, astronomers and physics know light as ***electromagnetic radiation***.

The part of the ***electromagnetic spectrum*** humans can see is called the ***visible spectrum***

Why electromagnetic? Electromagnetic refers to the physical nature of light. We now understand that light really is a coupling between an oscillating electric field and magnetic field. It is a fundamental piece of a branch of physics knowns as electromagnetism because it deals with electric and magnetic parts, which are related and inseparable from one another.

Why spectrum? Light can be divided up on a scale between two extremes, from radio waves to gamma rays. The visible part of this division you can see using a prism. What aspect of light defines the scale? The division of the spectrum can be set along the ***energy***, ***wavelength***, or ***frequency*** of the light. All three of these depend uniquely on each other so they are just different ways of doing the same thing.

The electromagnetic spectrum of light. 𝛄 is the Greek letter gamma. Image credit: Wiki- Creative Commons



*Figure 1. The electromagnetic spectrum of light. 𝛄 is the Greek letter gamma. Image credit: Wiki- Creative Commons*

### I. What do you see?

There are three images associated with this activity, Kemble’s Cascade, Castor and Pollux, and 25 brightest stars. Look at each of them and see what you notice about stars. List as many properties or ideas as you can.

Discuss your reasoning with your instructor at this point

### II: Explore Blackbody Radiation

Open the PhET Simulation “Blackbody Spectrum” With this simulation, you will observe how an object’s temperature relates to the light (radiation) it emits. Remember that all objects with a temperature emit radiation, and that dense objects emit thermal radiation, which in an ideal case is called ***blackbody radiation***.

On the left, the simulation displays a graph of the power, that is, how much energy the light delivers in each second vs. the wavelength. The rainbow shaded portion is the visible spectrum. On the right is a slider to set the temperature. There are check boxes to display the values at the peak of the spectrum, labels for parts of the spectrum, and the intensity, or brightness, of the light source. At the top center is a little star that shows you what the source would look like at that temperature.

A. Begin by just experimenting with the temperature. How does the spectrum change as you vary the temperature? What is the simplest way to use the spectrum to determine how hot the source is? There are +/- buttons on each axis that you can use to zoom in and out.

The temperature of stars in the universe varies with the type of star and the age of the star among other things. By looking at the shape of the spectrum of light emitted by a star, we can tell something about its average surface temperature.

B. If we observe a star's spectrum and find that the peak power occurs at the border between red and infrared light, what is the approximate surface temperature of the star? (in degrees K[[1]](#footnote-1))

C. If we observe a star’s spectrum and find that the peak power occurs at the border between blue and ultraviolet light, what is the surface temperature of the star? (in degrees K)

D. Incandescent and halogen light bulbs operate at 2500 K. What is the wavelength at which the most power is emitted for a light bulb operating at 2500 K?

E. Explain why regular incandescent and halogen bulbs formerly used for household lighting waste a lot of energy. Be sure to include your reasoning. You can see spectra for typical LEDs here: <https://en.wikipedia.org/wiki/Light-emitting_diode#/media/File:RGB_LED_Spectrum.svg> LEDs are much more efficient because they don’t use heat to generate light.

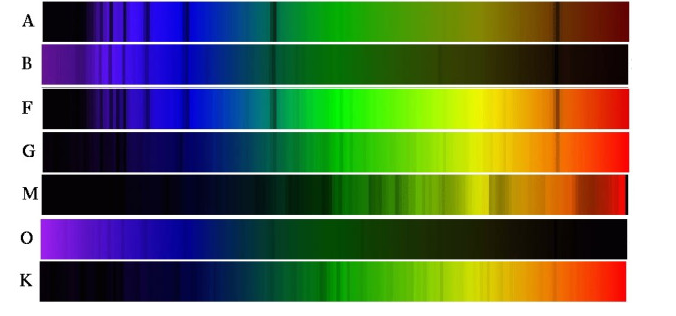
F. The constellation Orion is easy to find in the winter sky. Just look for the three belt stars. Orion supposedly looks like a person who is walking across the sky. Behind him there is a very bright star. This star is called Sirius (supposed to be Orion’s dog). Sirius is actually a binary star. The two stars are designated A and B. B is a white dwarf and is far too dim to be seen without a telescope.

Turn the temperature up to that of Sirius A. Can you explain why Sirius is a bright bluish color (it is the first one in the 25 brightest stars image if you want to take a look)? When we look at it, are we seeing the peak in its spectrum?

G. As you played around with the temperature slider, how did the color of the simulated star image change? Judging from the graph, how did the brightness of the star change? All other things being equal, which should be brighter, red stars or blue stars?

H. Look at the 25 Brightest Stars image again. Is it consistent with what you just concluded about the brightness of red vs. blue stars? What other properties could be factors in determining the brightness that we see from Earth?

I. These are some typical star spectra. Put them in order of temperature, from highest to lowest, and explain your reasoning.



Discuss your reasoning with your instructor at this point

### III: The Thermal Radiation Laws: Wien’s Law and Stefan-Boltzmann’s Law

Open the University of Nebraska – Lincoln Astronomy Simulation “Blackbody Curves (NAAP). – Blackbody Explorer” With this simulation, you can create a blackbody curve for any temperature between T = 3,000 K and T = 25,000 K. The simulation allows you to create multiple blackbody curves on the same set of axes, identify the wavelength where the blackbody curve has the highest intensity (a.k.a., the “peak wavelength”), see the total area under the blackbody curve, and examine photometric filters.

A. Using the temperature slider, examine blackbody curves for the following temperatures and fill out the peak wavelength and area under the curve in the table below. For the “Peaks in what part of the EM spectrum,” all peaks will occur either in the Infrared, Visible, or Ultraviolet portion of the electromagnetic spectrum. If Visible, put the color of light instead of just “Visible.”

***Table 1. Blackbody Curve Data***

|  |  |  |  |
| --- | --- | --- | --- |
| **Temp [K]** | **Peak  Wavelength[µm]** | **Blackbody  Area [W/m2]** | **Peaks in what**  **part of EM spectrum?** |
| **3000** |  |  |  |
| **5000** |  |  |  |
| **7500** |  |  |  |
| **10000** |  |  |  |
| **12,500** |  |  |  |
| **15,000** |  |  |  |
| **20,000** |  |  |  |
| **25,000** |  |  |  |

b. Transfer this data table to Excel. To enter scientific notation in Excel, you use E to separate off the power from the coefficient. For example, if you want to enter 2.77x105, you would type 2.77E5.

Make two graphs: the *peak wavelength in microns vs the temperature* in Kelvin of the blackbody, and the *total area under the blackbody curve in Watts per square meter vs the temperature* in Kelvin of the blackbody. These plots demonstrate the relationship between an object’s temperature and what wavelength of light they emit most of, and the relationship between temperature and how much total energy they emit.

C. You will now explore the relationship between blackbody temperature and at what wavelength the blackbody curve reaches its maximum value, i.e., the ***peak wavelength***.

On the left graph (peak wavelength vs temperature), add a trendline.

Try fitting the data with each function. For Polynomial, try order 2, a quadratic equation. Which function provides the best fit to the data?

Best fit to data is with a function.

D. Choose the option “Display Equation on chart” to get the equation relating the peak wavelength to the temperature. Write the equation in the space below. Is the peak wavelength proportional to or inversely proportional to the temperature?

The graph’s y-axis is peak wavelength measured in microns [µm]. Let’s label that 𝜆p. The graph’s x-axis is temperature measured in Kelvin [K]. Let’s label that T. Rewrite the equation replacing y with 𝜆p and x with T.

This equation is known as ***Wien’s Displacement Law***, often just “***Wien’s Law,”*** which relates the temperature of a blackbody to the peak wavelength of that object’s blackbody spectrum.

Congratulations, you just discovered one of the two thermal radiation laws! Let’s now find the other one.

You will now explore the relationship between blackbody temperature and the total area under the blackbody curve. The total area under the blackbody curve is really a measure of all the light an object is emitting every second. Particles of light come in discrete packets (quanta) called ***photons***, such that a photon of a specific wavelength carries a specific amount of energy. Thus, the area under the blackbody curve is just counting up all the photons over all of the wavelengths, or in other words, it is counting up all the energy the blackbody is emitting. This total is given in amount of energy measured in Joules per second [J/s], or Watts [W], being emitted by every square meter (m2), an area, of the blackbody’s surface.

E. On the total area vs temperature graph, right click on one of the data points and choose “Add Trend Line.” Again, try all the options including a quadratic, i.e., a polynomial order 2 equation.

Best fit to data is with a function.

F. Choose the option “Display Equation on chart” to get the equation relating the total area under the curve (energy per square meter) to the temperature. You may need to change the format of the number to “scientific” to see the value of the constant. This can be done by double left-clicking the equation box and selecting the tab that looks like a bar graph. Write the equation.

Discuss your reasoning with your instructor at this point

G. The graph’s y-axis is total energy per second per area measured in W/m2, a quantity called ***Flux, F***. Astronomers call the total power (energy per second) an object emits over the entire surface is called Luminosity, L. Luminosity is measured in Watts [W]. So, the y-axis is the object’s luminosity divided by the total surface area of the object, A.

Let’s, therefore, replace *y* with L/A.

The graph’s x-axis is temperature measured in Kelvin [K]. Let’s label that T. Rewrite the equation replacing y with L/A and x with T.

H. Astronomers often want to know the luminosity (total energy per second) an object like a star emits. Since a star emits light equally from all parts of its surface, to get total energy, we need to multiply both sides of the equation by the surface area, A. On the left-hand side of the equation that leaves us with L, and on the right-hand side, we multiply everything by A. Rewrite the equation from (iii) as L equals…

I. This equation is known as the Stefan-Boltzmann Law, which relates the temperature of a blackbody to the total amount of energy that object is emitting, or rather, its luminosity. The constant in this equation is called the Stefan-Boltzmann constant, which is usually written as 𝜎B instead of actually writing out the number.

The true value of the Stefan-Boltzmann constant is 𝜎B = 5.67 × 10-8' W m-2 K-4. Compare the number you got to that. Is it the same? If not, you may want to check your “Blackbody Area” data in Table 1.

J. In Part 2 question H, we noticed that there are both red and blue bright stars, but none of them are close to us so distance cannot really explain that. If the brightness just depended on the temperature, then the red ones would be very dim. But now, given the Stefan-Boltzman law, what else does the brightness depend on? What can you say about the size of the bright red stars compared to the bright blue ones?

Discuss your reasoning with your instructor at this point

### IV: Application to the Stars

This task moves away from the UN – Lincoln Astronomy Simulations and it has you apply the two thermal radiation laws you developed in the previous section to actual spectra of stars. Below are the spectra of several different stars, each one with a different temperature. The stars’ spectra are not perfect blackbodies because of the cooler gas above the “surface” of the star absorbing light at specific wavelengths. Understanding what causes these absorptions at specific wavelengths is the goal of a future activity. For now, you just need to focus on the general blackbody shape you can still discern.

A. To the best of your ability, identify and record the peak wavelength of each of the stars’ spectra. Using that peak wavelength, determine the surface temperature of each star.

|  |  |
| --- | --- |
| stars’ spectra  1000  900  800  700  600  500  400  300    Wavelength (nm) | stars’ spectra  1000  Wavelength (nm)  900  800  700  600  500  400  300 |
| Peak Wavelength in nm: | Peak Wavelength in nm: |
| Temperature: | Temperature: |
| stars’ spectra  1000  500  600  700  800  900  Wavelength (nm)  300  400 | stars’ spectra  1000  300  400  500  600  700  800  900  Wavelength (nm) |
| Peak Wavelength in nm: | Peak Wavelength in nm: |
| Temperature: | Temperature: |

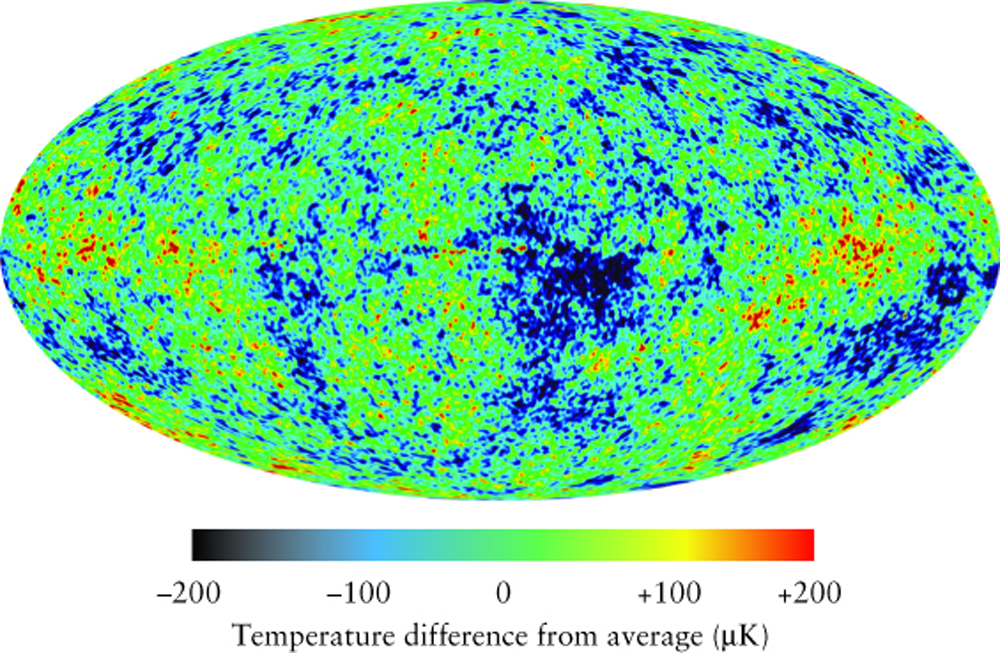
B. Determine the total luminosity (energy output every second) of the four stars and compare them to our Sun. The luminosity of the Sun is

Luminosity of the Sun: LSun = 3.828 x 1026 Watts.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Star** | **Radius [m]**  **R** | **Surface Area**  **4πR2** | **Luminosity [W]**  **LStar** | 𝑳𝒔𝒕𝒂𝒓/***Lsun*** |
| G0V | 7.6 x 108 m |  |  |  |
| K4V | 4.5 x 108 m |  |  |  |
| K0V | 5.5 x 108 m |  |  |  |
| F5V | 8.7 x 108 m |  |  |  |

C. The universe has a temperature. It is filled with blackbody radiation with a temperature of 3 K. In what part of the spectrum would the peak wavelength be? (Discovery of this radiation won a Nobel prize in the 1960’s. The discoverers worked for the phone company (the ONLY phone company back then) and were just trying to eliminate noise from long distance transmissions.)

D. It used to be thought that the cosmic background was all the same temperature, perfectly smooth and uniform. Just a few years ago, measurements became accurate enough to see temperature variations. The picture below shows those variations in false color, where the colors are coded by how far above or below 3 K they vary (in units of microkelvin; A microkelvin (μK) is 10-6 K – a millionth of a Kelvin). What are the max and min values of the temperature and the peak wavelength? What part of the electromagnetic spectrum is this? These variations were caused by slightly higher and lower concentrations of matter in the very early universe.



Discuss your reasoning with your instructor at this point

**Questions**

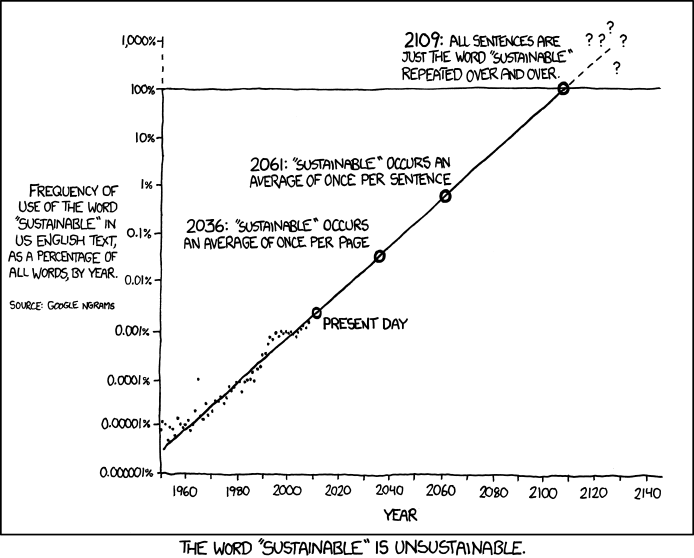
There are two things you can do with a curve fit: interpolation and extrapolation. Interpolation refers to using your curve fit to find values in between your measurements. That is, in the curve fits we have been using, finding the peak wavelength and luminosity of a star at 4000 K even though we made no measurements at that temperature. But we did make measurements on either side, at 3000 K and 5000 K. Interpolation is finding a value in the midst of your data. When your TV upscales data to a higher resolution or frame rate, it is using interpolation, finding a value between the original pixels or between the original frames.

A. Do you think interpolation is generally justified or mostly questionable? Why? Use Wien’s Law and Stefan-Boltzman laws as examples.

Extrapolation is using your curve fit to find a value beyond the end of your data. For instance, finding peak wavelength and luminosity of a star with a temperature of 1000 K or 50,000 K.

B. Considering Wien’s Law and the Stefan-Boltzman law, do you think either interpolation or extrapolation are justified? Would you rely on the values you would get at 1000 K and at 50,000 K? Think about the physics in these equations to explain your answer.

C. Here is an example of extrapolation taken from an XKCD comic. This is clearly a bad use of extrapolation, but why? What is the difference between extrapolating the thermal radiation laws and extrapolating the word count of “sustainability?” What else do you need to know to justify extrapolation in one case but not the other?



D. The British newspaper *The Mail on Sunday* has been heavy into climate change denial for some years. In 2013, they published the graph below, using it to argue that global warming stopped in 2008. What do you think about the validity of this graph and the conclusions based on it? And you don’t get to use what we know happened later to criticize this argument.

A graph showing the temperature of the earth change from 1960 -2020



For the record, you can see what happened after 2008 here:

<https://www.yourweather.co.uk/news/science/2021-forecast-to-be-among-hottest-years-on-record-temperature-world.html>

The way the Mail used data is called cherry picking.

E. We’ve been looking at stars because they emit a lot of visible light. Star temperatures are a few thousands to a few tens of thousands of. Planets are generally a few hundred K. In what part of the spectrum do you think they would emit the most light?

1. Degrees Kelvin are degrees Celsius except for one thing. Zero C is the freezing point of water. Zero K is absolute zero, the lowest possible temperature, at which all the heat has been removed. This is -273 C (and over -400 F). [↑](#footnote-ref-1)