Activity 10: Color, Temperature, and Size [1]

Materials:

Computer with Internet connection
Visible spectrum in color (tinyurl.com/276w523d)

Last week we learned about how astronomers can use the light that reaches us from distant objects to determine the composition of those objects. Today we will continue to unravel the detective work done by astronomers as we see how the light we receive from distant objects also tells us about their temperature and size.

Part 1: Blackbody Spectrum

Last time, we saw that a hot, dense object (like a light bulb or a star) will emit a **continuous spectrum** of light. In this first Part we will take a closer look at the continuous spectrum and what we can learn from it.

A continuous spectrum is also called a **blackbody spectrum**. Its name comes from the fact that a black object doesn't reflect any light, and so a "blackbody spectrum" is the spectrum that a hot object would emit *even if it were black* (i.e., even if it doesn't reflect any light at all).[2]

Last time, we saw *which colors* were emitted by the light bulb (all of the "colors of the rainbow"), but we didn't talk about *which* colors were *bright* and which ones were *dim.* Today we are going to focus on the brightness that is emitted at various wavelengths. The scientific term for the brightness of radiation is **intensity**.

A **spectral curve** is a graph that shows the *intensity* of radiation emitted at *each wavelength* (or equivalently, at each frequency). This looks like a graph with intensity on the y-axis and wavelength on the x-axis.

STEP 1: Consider the sample spectral curve below for an object that's emitting a continuous spectrum of radiation in the visible light wavelengths.

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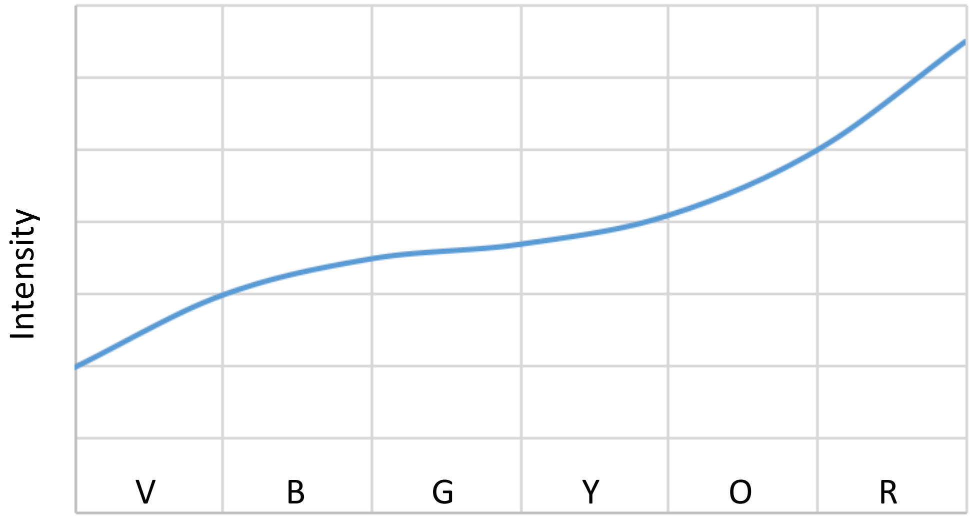
[1] Parts of this Activity were adapted from Prather et al, *Lecture-Tutorials for Introductory Astronomy Third Edition.*

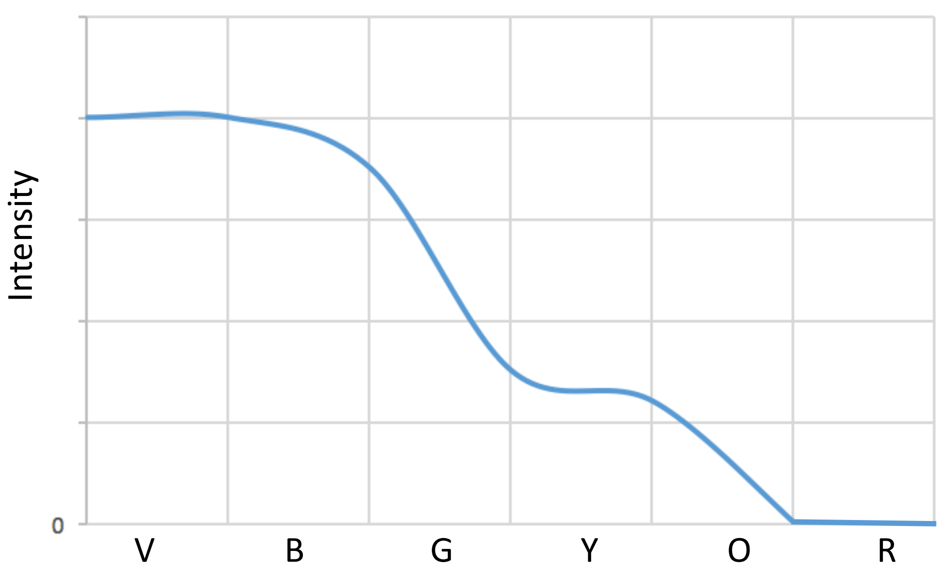
[2] However, the object doesn't always appear black because it can emit radiation of its own. So blackbodies aren't really black. Don't let the name confuse you; it is derived from the idealized scenario in which an object is a perfect absorber of light. A light bulb, the Sun, and even yourself can all be modeled as blackbodies.



Is the x-axis of this graph in order of *increasing wavelength* or in order of *increasing frequency* (going left to right)?

Which color of light is being emitted with the greatest intensity by this object?

Consider the spectral curve below. What colors are present (i.e., being emitted by the object)?



If you were to look at this object with the unaided eye (i.e., without a spectroscope), do you think it would appear more reddish or more bluish? Why?

Now that we've had a little practice looking at spectral curves, let's look at some spectral curves for real objects.

STEP 2: On your computer, open the simulation at the URL below. Or, go to phet.colorado.edu, hover over "Simulations" on the menu and click on "Physics" in the menu that drops down. Scroll down until you see "Blackbody Spectrum" and click on it.

https://phet.colorado.edu/en/simulation/blackbody-spectrum

Click on the simulation to start it. When the simulation opens, notice that the visible portion of the electromagnetic spectrum is highlighted for you with the colors of the visible spectrum (i.e., a rainbow).

STEP 3: Using the temperature slider, set the temperature to 600 K -- the temperature of a very hot oven. This equals about 620 °F. [3]

The spectral curve is the red line, which may look like a flat line right now.

Notice that you can adjust the zoom on both the X axis and Y axis. Try adjusting them so that you can see the shape of the spectral curve. Hint: try a Y axis with a max value of $1x10^{-3}$ and an X axis with a max value of 12.

At what wavelength is the oven emitting radiation at the greatest intensity? That is, *what wavelength on the x-axis lines up with the peak of the curve*?

To make this easier to read, click on the check box next to Graph Values. You can now click and drag the white dot around until it is positioned on the peak (if it's not already there).

Notice that the x-axis is given in units of micrometers (μm), each of which is 10^{-6} or one millionth of a meter.

Write down the approximate wavelength for the peak. Round to the nearest micrometer (μm).

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[3] Does that sound hot for an oven? Pizza ovens in Naples, Italy (the birthplace of pizza) that cook pizzas in the traditional style operate at a temperature of 1000 °F

One micrometer contains 1,000 nanometers. What is this spectral curve's peak wavelength in nm?

Is the oven emitting much radiation in the visible light wavelengths? How can you tell from the spectral curve?

However, you've probably noticed that the heating elements on your stove *do* start to glow (and therefore, give off visible light) when they get hot. Let's see why this happens.

STEP 4: Set the simulation temperature to that of a very hot stovetop heating element, which is about 2000 K.

You may need to adjust your zoom again. This time try using an X-axis with a maximum of 3 and a Y-axis with a maximum of 0.8.

What wavelength of light is most intense as emitted by this heating element? That is, what wavelength on the x-axis lines up with the peak of the curve? Round to the nearest 1/10 of a μm.

Is the heating element emitting any radiation in the visible light wavelengths? Increase the zoom of the X-axis once (so that the max is 1.5) to see it a little better.

If you were to look at this heating element with the unaided eye (i.e., without a spectroscope), what color would it appear to be, and why that color? Remember, the unaided eye can only see visible wavelengths!

Does your previous answer agree with the color that you typically see when a stovetop gets hot?

If the stovetop were to continue to get hotter, what color would it be? Try increasing the temperature to 2500 K and focus on the spectral curve as it relates to the visible portion of the spectrum.

STEP 5: Now let's take a look at a light bulb. The tungsten filament of a standard incandescent light bulb reaches a temperature of about 3000 K. Set your simulation temperature to 3000 K. You will probably have to zoom out on the Y-axis to see the shape of the spectral curve.

Remember: infrared is the portion of the spectrum that's just beyond red, and ultraviolet is the portion of the spectrum that's just beyond violet.

Does the light bulb emit any UV? A lot, a little, or none at all? How can you tell?

Find the peak wavelength (i.e., the *point on the x-axis at which the spectral curve has its peak in the y-direction*) for the light bulb. Click the check box next to "Labels". In what part of the spectrum (gamma, x-rays, UV, visible, IR, microwave, radio) is this peak wavelength?

If a light bulb's purpose is to emit visible light, is this tungsten-filament light bulb the most energy efficient way of doing so? Why or why not?

STEP 6: OK, let's take a look at the Sun! The surface temperature of the Sun is about 5800 K. Note that this is the *surface* temperature, which we are interested in because it's the part of the Sun that emits the light that reaches us on Earth (the Sun's surface is also called the **photosphere**). However, this is very cool compared to the *internal* temperatures of the Sun, which at the core can reach nearly 30 *million* K.

Set your simulation temperature to 5800 K. Zoom out on the Y-axis as needed.

What type of electromagnetic radiation (gamma, x-rays, UV, visible, IR, microwave, radio) does the Sun emit more than the rest?

Challenge question: Why does your previous answer make sense from the perspective of *evolutionary biology* and the eyes of humans and other animals on Earth? *Hint:* Which came first: the Sun, or animals on Earth?

Does the Sun emit any UV? More or less than was emitted by the light bulb? Does this match your expectation, and if so, how?

Important Note: You have probably noticed by now that the peak of the spectral curve gets taller and shorter as you change the temperature. This is true, but there are other reasons why the peak could be higher for some objects (as we'll see in Part 3). However, the *x position* of the peak of the spectral curve depends *only* on the temperature.

> Therefore, if you want to compare the temperature of two spectral curves, you must compare the ***x-positions*** *of their peaks*.

STEP 7: Using the simulation, conduct your own experiment to answer SQ1.

SQ1:

a) As the temperature of an object *increases*, what happens to the peak wavelength of radiation emitted by that object? Does the peak *wavelength* (which you read from the x-axis) increase, decrease, or stay the same?

b) As the temperature of an object *decreases*, what happens to the peak wavelength of radiation emitted by that object? Does the peak *wavelength* (which you read from the x-axis) increase, decrease, or stay the same?

c) Looking back at (a) and (b), what kind of relationship exists between the temperature of an object and the peak wavelength of radiation emitted by that object?

> The above relationship that you wrote down in part (c) is called **Wien's Law**, after the German scientist that discovered it in 1893 (his name is pronounced like *VEEN*).
>
> With the help of Wien's Law, we will be able to find the temperature of distant objects.

Part 2: Wien's Law

Now that we've seen the relationship called Wien's Law, we can start to identify the temperatures of stars based on their spectral curves. Before we begin, write down Wien's Law below in your own words.

Look at the spectral curves below of stars that we've named C, D, E, and F.

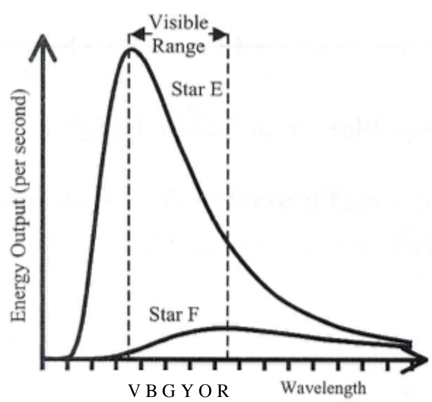


Figure 1

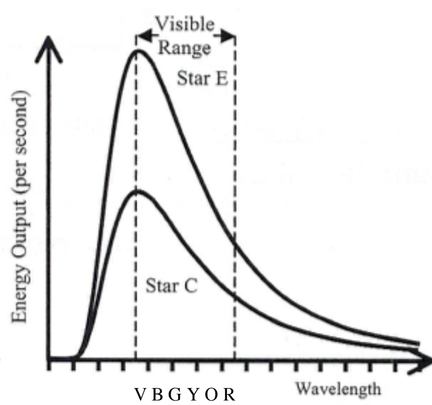


Figure 2

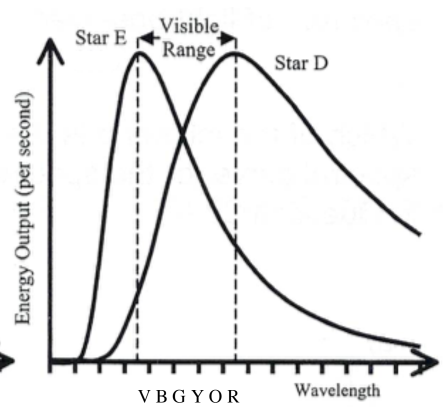


Figure 3

To make sure we've oriented ourselves properly with the figures above, how is the x-axis ordered with respect to wavelength: from left to right is the *wavelength* increasing or decreasing?

STEP 1: Compare stars E and D in Figure 3. Which one, if either, has the higher temperature? How can you tell? *Hint:* Use Wien's Law!

STEP 2: Compare stars E and C in Figure 2. Which one, if either, has the higher temperature? How can you tell?

Which one (E or C) has the highest *maximum intensity*?

STEP 3: Compare stars E and F in Figure 1. For each characteristic below, select the correct response on the right.

Characteristic	Responses			
Peaks at a longer wavelength	Star E	Star F	They peak at the same wavelength	
Has a lower temperature	Star E	Star F	They have the same temperature	
Looks red	Star E	Star F	They both look red	Neither looks red
Looks blue	Star E	Star F	They both look blue	Neither looks blue
Has the highest maximum intensity	Star E	Star F	The have the same maximum intensity	

STEP 4: Wien's Law can be written as a very simple mathematical equation. For an object at a temperature *T*, its peak emission wavelength λ_{max} is given by:

$$\lambda_{max} = \frac{b}{T}$$

where *b* is a constant equal to 0.0029 mK (milli-Kelvin).

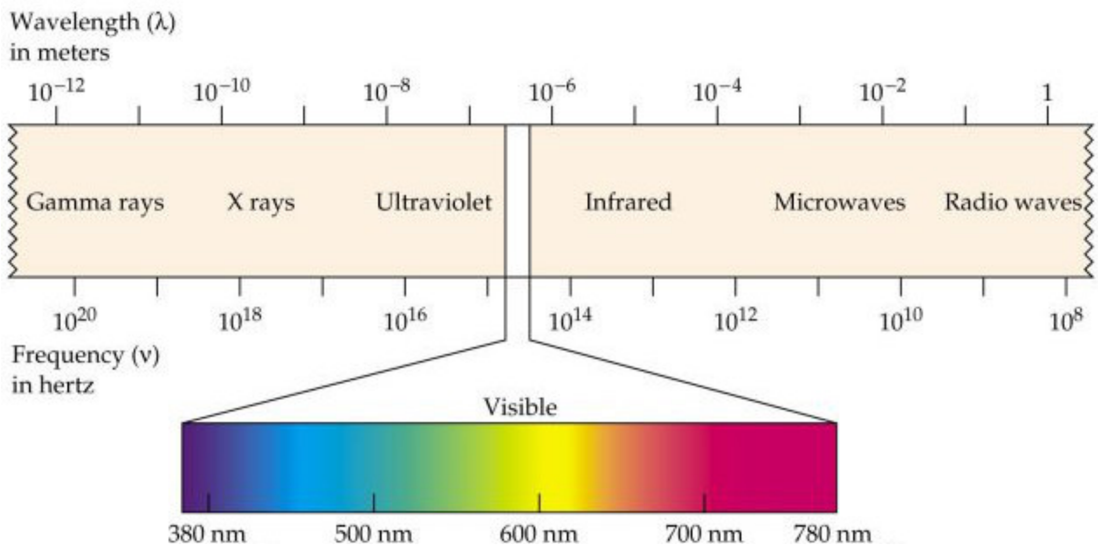
Looking at the equation: as *T* increases, what happens to λ_{max} (recalling that *b* is a constant)? Does this agree with what you concluded earlier about the relationship between temperature and peak wavelength?

On your computer, open the website at the URL below.

www.cactus2000.de/uk/unit/masswvg.shtml

This website uses the above Wien's Law equation to compute any missing quantity. That is, you input *any one* quantity and hit "calculate" and it will calculate *all of the other* quantities.

STEP 5: Using the website above and the EM spectrum below, answer the following questions.



SQ2: What is the wavelength of peak emission for our Sun, which has a temperature of 5800 K? What color is this (full-color visible spectrum is here: tinyurl.com/276w523d)?

What is the wavelength of peak emission for an object with a temperature of 8000 K? What portion of the spectrum is this?

SQ3: Through your telescope, you see a star that is a bright shade of blue. Use the Wien's Law calculator to estimate the temperature of that star. How does this compare to the Sun's temperature of 5600 K?

A warm-blooded animal (such as yourself) has a body temperature of about 310 K. What is *your* wavelength of peak emission? What is the corresponding frequency?

Find *your* peak emission frequency on the electromagnetic spectrum. (Note: e+7 at the end of a number means x10^7, and 1 MHz = 1 million Hz = 10^6 Hz, therefore e+7 MHz = 10^{13} Hz). In what portion of the spectrum is this frequency?

SQ4:

(a) Do you and I emit radiation? If yes, then why can't we see each other's radiation?

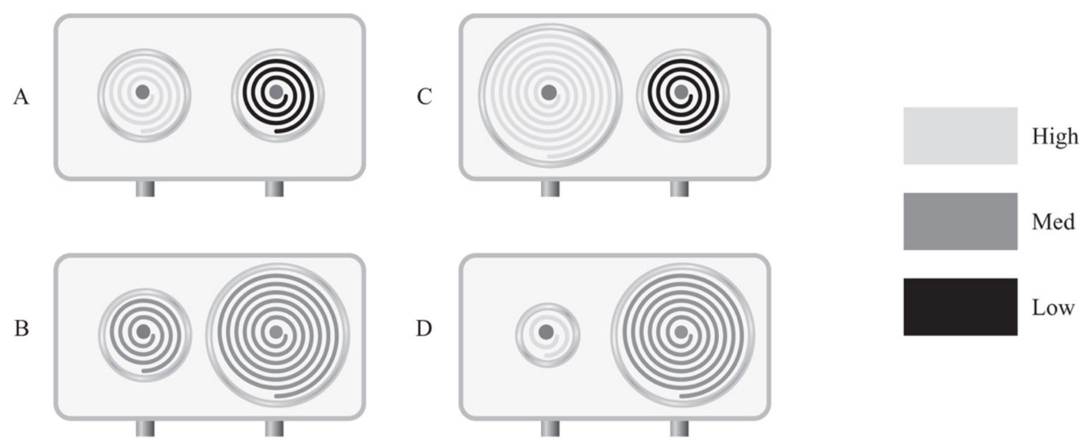
(b) If you wanted to design a pair of goggles that could see warm bodies even in absolute darkness (i.e., in the absence of *all visible light*), which part of the spectrum should your goggles detect? Explain your reasoning.

Part 3: Luminosity and Size

In this Part we will discuss how the information about a star's temperature (which we can deduce using the methods of Parts 1 and 2) will also allow us to deduce the size of the star. First, we will work from an analogy.

Imagine you are comparing the ability of electric plates of different sizes and temperatures to fully cook two identical large pots of spaghetti. All the pots are as large as the largest hot plate. The shading of each hot plate is used to illustrate its temperature. The darker the shade of gray, the cooler the temperature of the hot plate.

STEP 1: For each of the four pairs (A, B, C, D) of hot plates shown below, circle the hot plate in each pair that will cook the large pot of spaghetti more quickly. If there is no way to tell, state that.



If you use two hot plates of the *same size*, can you conclude that the hot plate that can cook a large pot of spaghetti first is at the higher temperature? Which lettered example above supports your answer?

If you use two hot plates at the *same temperature*, can you conclude that the hot plate that can cook a large pot of spaghetti first is larger? Which lettered example above supports your answer?

If you use two hot plates of *different sizes* and *different temperatures* (hint: there are two such situations from the lettered examples above), can you always conclude that the hot plate that can cook a large pot of spaghetti first is at a higher temperature? Which lettered example above supports your answer?

STEP 2: The time it takes for the spaghetti to cook is determined by the rate at which the hot plate transfers energy to the pot. This rate is related to both the temperature and the size of the hot plate.

SQ5: For stars, the rate at which energy is given off is called its **luminosity**. Working by analogy from the hot plates, complete the sentence below:

A star's luminosity can be increased by

____

and/or by

____.

STEP 3: Now we have related *three* quantities: luminosity, temperature, and size.

If two hot plates have the same temperature and one cooks the pot of spaghetti more quickly, what can you conclude about the sizes of the hot plates?

Similarly, if two stars have the same temperature and one is more luminous (i.e., has a greater luminosity), what can you conclude about the sizes of the stars?

If two stars have the *same temperature* and are the *same size*, which star, if either, is more luminous?

If two stars are the same size, but one has a higher temperature, which star, if either, is more luminous? Explain your reasoning.

STEP 4: Looking back at Figure 3 in Part 2 of the spectral curves of various stars (pg 7), look again at the graph comparing stars D and E.

Those graphs depict intensity on the y-axis, and remember that intensity is the brightness (or amount of energy) emitted by the star.

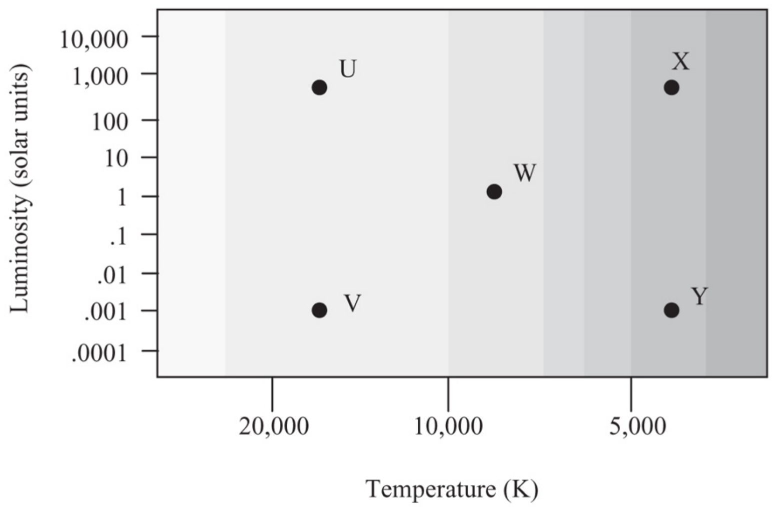
How do the temperatures of D and E compare?

How does the overall intensity (i.e., the luminosity) of D and E compare?

Based on your above answers, and the conclusions you drew about luminosity, temperature, and size in Step 3, which star (D or E) is smaller and which is larger? How can you tell?

Part 4: H-R Diagrams

Below is a **Hertzsprung-Russell diagram** (or **H-R diagram**). An H-R diagram is a graph that plots the luminosity of a star on the Y-axis and the temperature of the star on the X-axis.



The Y-axis is in units of *Sun Luminosities*. 1 is equal to the Sun's Luminosity, 10 is equal to 10 times the Sun's Luminosity, etc. As you go from bottom to top on the Y-axis, what happens to the luminosity?

As you go from left to right on the X-axis, what happens to the temperature?

STEP 1: Using what you learned in Part 3, answer the following questions concerning the stars labeled U through Y.

Stars U and V have the same temperature. How can you tell?

Given that Star U is actually much more luminous than Star V, but they have the same temperature, what can you conclude about the size of Star U compared to Star V?

Star U has a greater temperature than Star X. How can you tell?

Given that Star X is actually just as luminous as Star U, what can you conclude about the size of Star X compared to Star U?

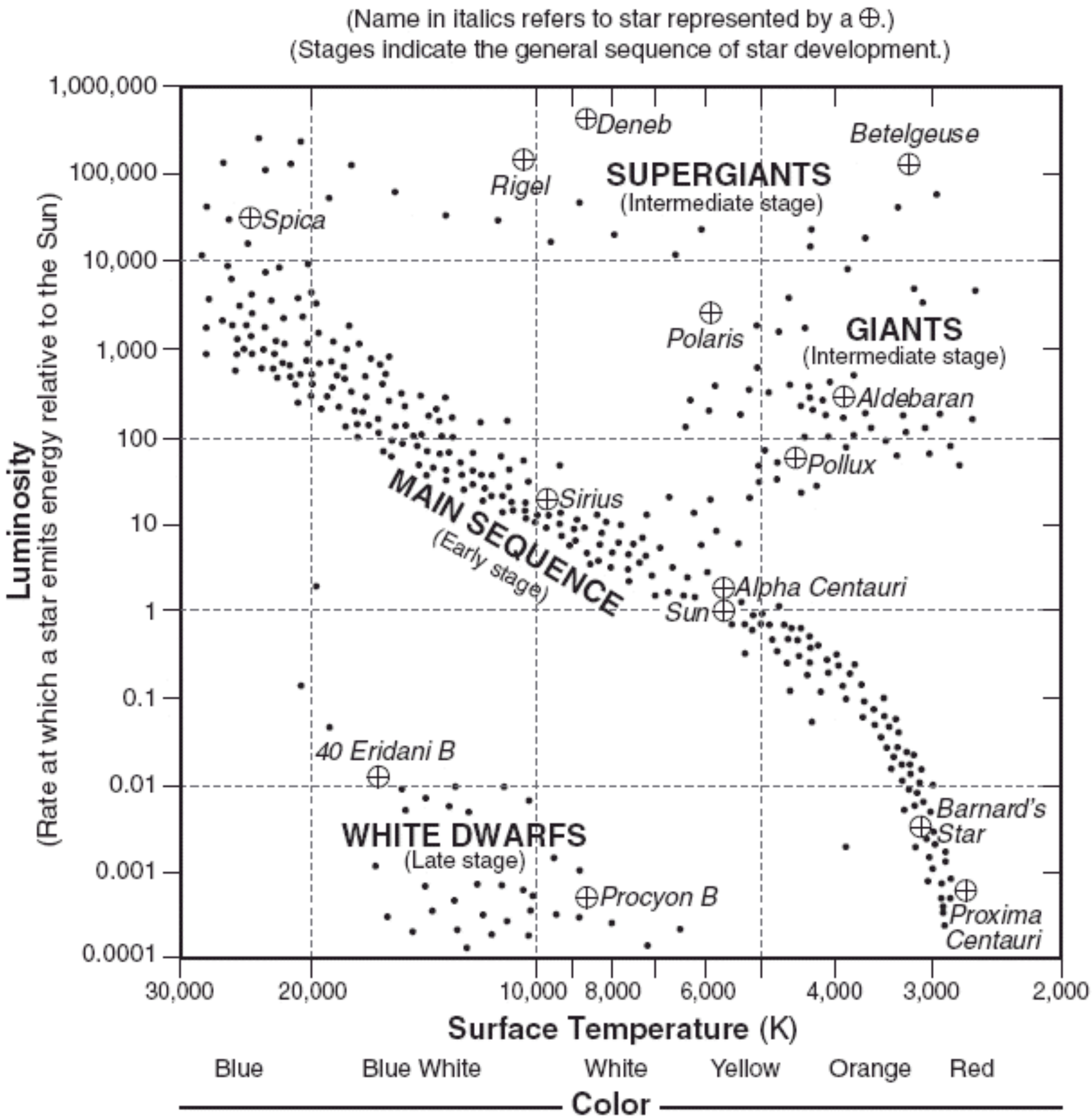
SQ6:

(a) Consulting the H-R diagram above, which star is larger, X or Y? Explain your reasoning.

(b) Which star is larger, Y or V? Explain your reasoning.

(c) On the H-R diagram, draw a “Z” at the position of a star smaller in size than star W but with the same luminosity. Explain your reasoning.

STEP 2: The H-R diagram below was constructed using data for actual stars. A few notable ones are labeled with the star's name.



Use the H-R diagram above to answer SQ7 and SQ8 below.

SQ7:

(a) Which star is *bigger*, the Sun or Alpha Centauri?

(b) Which star is *bigger*, Alpha Centauri or Polaris (the North Star)?

(c) Which star is *hotter*, Rigel or Betelgeuse?

(d) Which star is *bigger*, Rigel or Betelgeuse?

SQ8:

(a) Why do you think Procyon B and the other stars near it on the H-R diagram are called “dwarf stars”? Explain your reasoning.

(b) Why do you think Aldebaran and the other stars near it on the H-R diagram are called “giants”? Explain your reasoning.