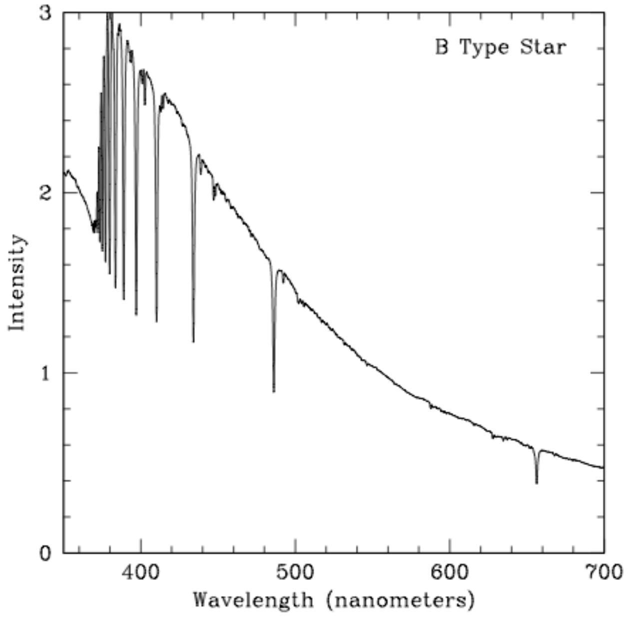
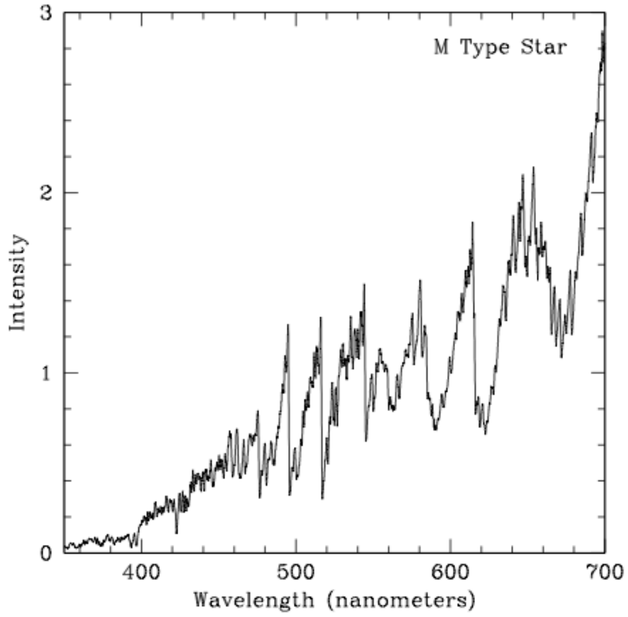
Project B:
Measuring Colors

In our daily lives, we frequently refer to the colors of objects. The English language contains an elaborate system of words to refer to the various colors we perceive. The words “lilac”, “mauve”, “eggplant”, and “burgundy” all refer to slightly different shades of purple. Through years of social experience, most people can agree on what shades of purple are assigned to these different words. However, while these words are evocative to fluent speakers of English, they do not give a “quantitative” (i.e. numerical) definition of color. A quantitative measurement of color would allow everyone to agree on the color of an object, rather than bickering over the subtle differences between “lilac” and “mauve”. Moreover, without a numerical measurement of color, one cannot construct a formula that connects color to other physical properties of an object. One cannot derive a temperature for a “lilac”, “mauve”, or “burgundy” colored star. Scientific work therefore requires a quantitative definition of “color”.

Different scientific fields use different methods to assign numerical values to colors. Although the details vary, all of the methods quantify the fraction of light that an observer receives from different wavelengths. As an example, below are the spectra of two stars. The star on the left is a hot B-star. The star on the right is a cool M-star.



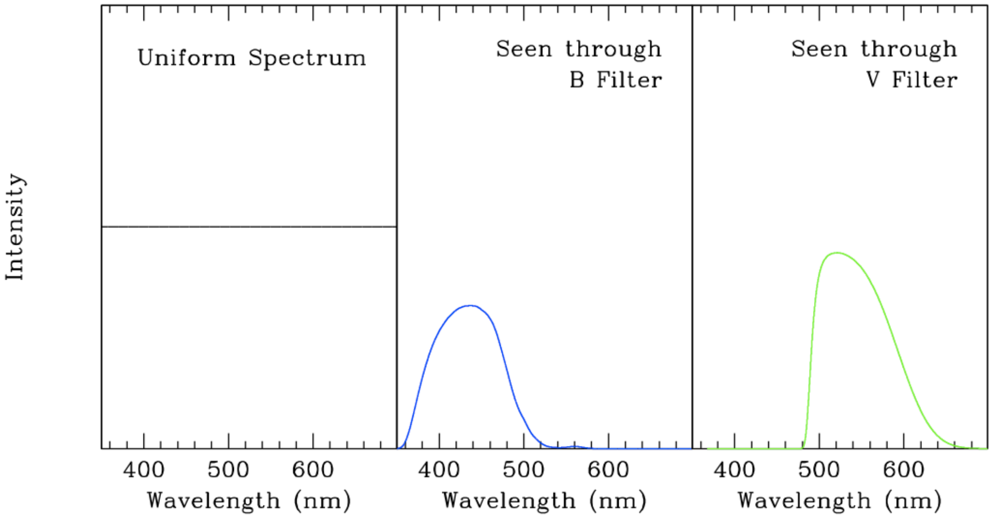


The B-star on the left would be perceived as “blue”, because it emits a much larger fraction of its light at short (blue) wavelengths than it emits at long (red) wavelengths. The M-star on the right would be perceived as “red”, because it emits a much larger fraction of its light at red wavelengths. Note that even if these stars were brighter or fainter, the fraction of light emitted at blue and red wavelengths would be the same, as long as the overall shape of the spectrum were constant. Thus, a B star will always be blue, no matter how bright it is.

To derive a color for the above stars, one could use the spectra to add up the energy of all the photons over some range of blue wavelengths (say, between 400 and 450 nanometers) and compare it to the energy of all the photons whose wavelengths fall within some range of red wavelengths (say, between 600 and 650 nanometers). By dividing the energy released in “blue” photons by the energy released in “red” photons, one could calculate a single number that would indicate the color of the star.

Unfortunately, access to telescopes is too limited to permit astronomers to measure spectra for every star. As an alternative to using a spectrum to add up photons with a specific range of wavelengths, one can take images of stars but only using light that falls within that same range of wavelength. To do so, astronomers take images of stars and galaxies through “filters”.

A filter is a piece of glass or plastic that is transparent to light of some wavelengths, but that is opaque to light of all other wavelengths[1]. One can build a filter that only lets in photons that have wavelenghts between 400 and 450 nanometers. If one puts that filter in front of a camera and takes an image, the photons that are received only come from that very narrow range of blue wavelengths. One can then take a second filter that transmits wavelengths between 600 and 650 nanometers, and take a second image. By comparing the relative brightnesses of stars and galaxies in the “blue” and “red” images, one can calculate the same single number that defines the “color” of the star.



The plots above show how two commonly used astronomical filters (called B and V) would affect the light you would receive from some object. The plot on the left shows an example spectrum of some object. This “uniform” spectrum is fairly boring and featureless. If you were to look at an object that emits this spectrum, you would receive the same amount of energy from photons of every color. Instead, if you viewed the same object through a B filter, which transmits only blue light, you’d receive only a fraction of the original photons, as can be seen

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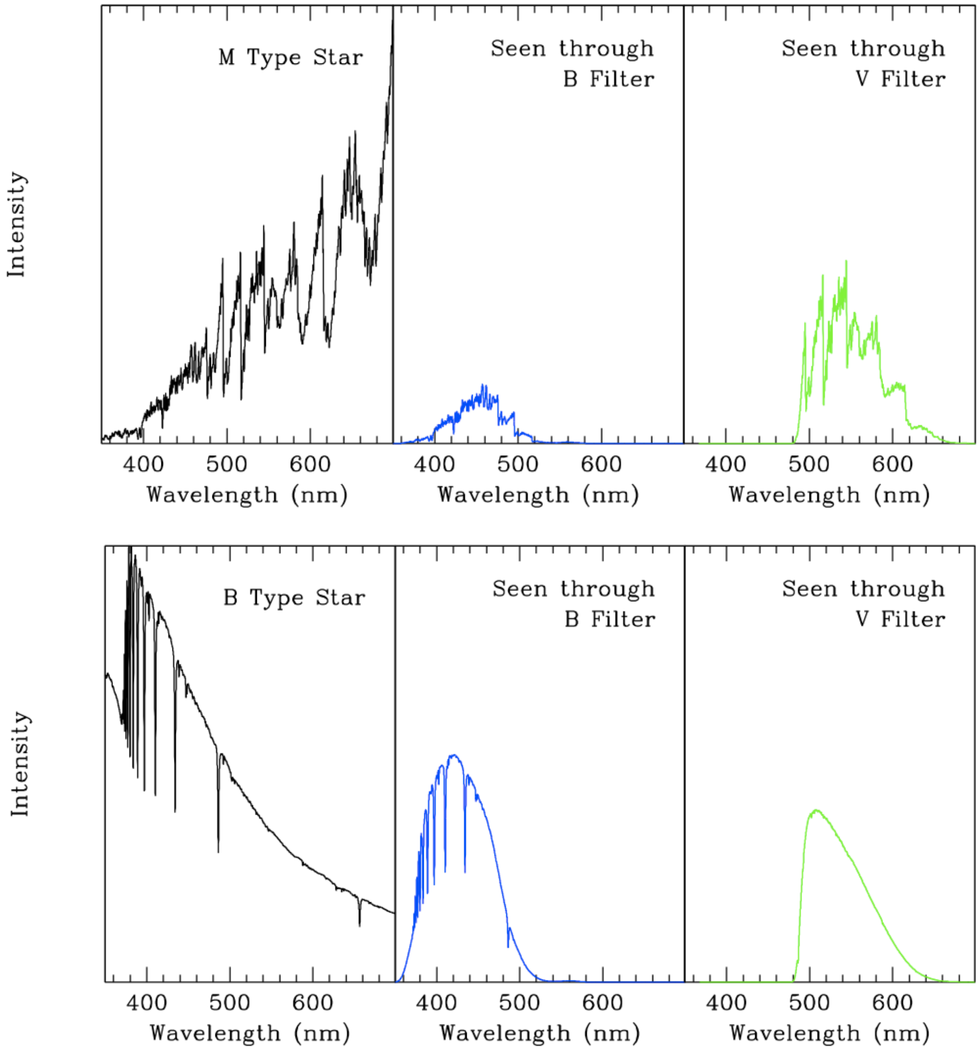
[1] Your sunglasses are a common example of a filter. They block ultraviolet light, and, if they are tinted, block selective colors of optical light as well. For example, if the lenses of your sunglasses have a reddish tint, it is because they preferentially transmit red wavelengths of light while blocking bluer wavelengths.

in the middle panel[2]. The right hand plot shows the photons you would receive if you viewed the same object through a V filter, which transmits only green and yellow light. Again, you'd receive only a fraction of the original photons, but in a different wavelength range than those you'd received through the B filter.

The plots below show a more complicated, realistic example, using the same B and V filters. The top row shows the spectrum of a B star viewed without a filter (left panel), through a blue B filter (middle) and a greenish-yellow V filter (right panel). The bottom row shows similar plots for a M star. For the blue B star, much more energy would pass through the B filter than the V filter. Thus, this star would look brighter at bluer wavelengths than at redder wavelengths. For the red M star, the situation is reversed, and the star would look brighter viewed through the redder V filter than the bluer B filter. If one divides the energy passing through the B filter by the energy passing through the V , one could derive a single number that reflected the color of these stars. In this project, you will experiment with this way of measuring color.



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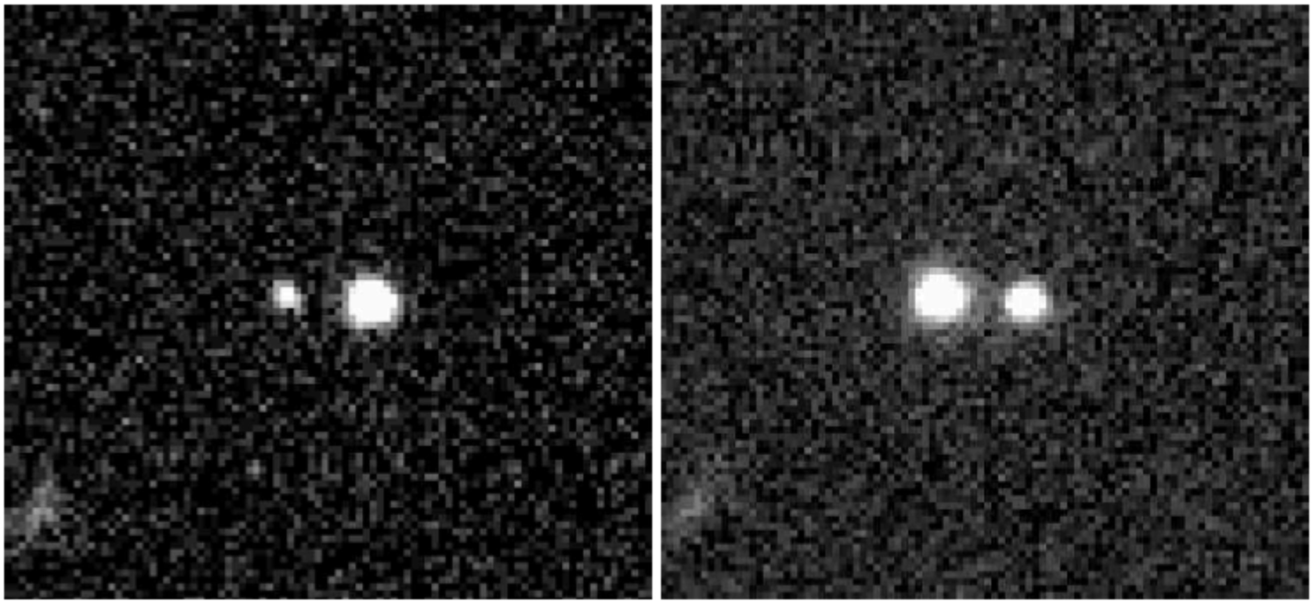
[2] It is difficult to build a filter that transmits 100% of the photons in some wavelength range and blocks all of the photons outside of the range. Instead, most filters transmit less than 100% of all photons, even at the wavelength where they are most transparent.

Below are two images taken of the same part of the sky. The image on the left is taken through a blue filter and the one on the right is taken through a red filter[3].



1. In the image on the left (taken through the blue filter), the star on the [left/right] is brightest.

2. In the image on the right (taken through the red filter), the star on the ________ [left/right] is brightest.

3. The star on the left has the largest fraction of its light emitted in the ___________ [red/blue] filter. It will therefore appear to be __________ [redder/bluer] than the star on the right.

4. The surface of the star on the ____________ [left/right] is hotter.

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[3] The dark background sky in these images looks grainy (like TV static), because the sky is not actually perfectly dark, and instead emits a trickle of photons which are detected by the sensitive digital camera that took these images. The diffuse smudge in the lower left is a distant galaxy.

Below are another two images of the same part of the sky. The image on the left is taken through a blue filter and the one on the right is taken through a red filter.

5. In the image on the left (taken through the blue filter), the star on the ______________ [top/middle/bottom] is brightest.

6. In the image on the right (taken through the red filter), the star on the ______________ [top/middle/bottom] is brightest.

7. The star on the ________________ [top/middle/bottom] has the largest fraction of its light emitted in the red filter, and will therefore appear to be the reddest of the three stars.

Procedure

At the end of this project you will find plots showing the spectra of O, B, A, F, G, K, and M-type stars. In each of these plots there are three panels. The left hand panel shows the true spectrum of the star. The middle panel shows the spectrum of the star if viewed through a B filter, and the right hand panel shows the spectrum of the star if viewed through a V filter. Superimposed on the right two panels is a grid, that will allow you to “add up” all the energy that you would receive from these stars if you viewed them through the B and V filters respectively. You will then use these measurements to calculate a numerical value of the color for the stars.

1. Using the grids on the plots for various stars, count up the number of boxes under the spectrum for the stars viewed through a B filter and V filter. The number of boxes will be proportional to the total energy received per second. Record your answers in the third and fourth columns of the table below.

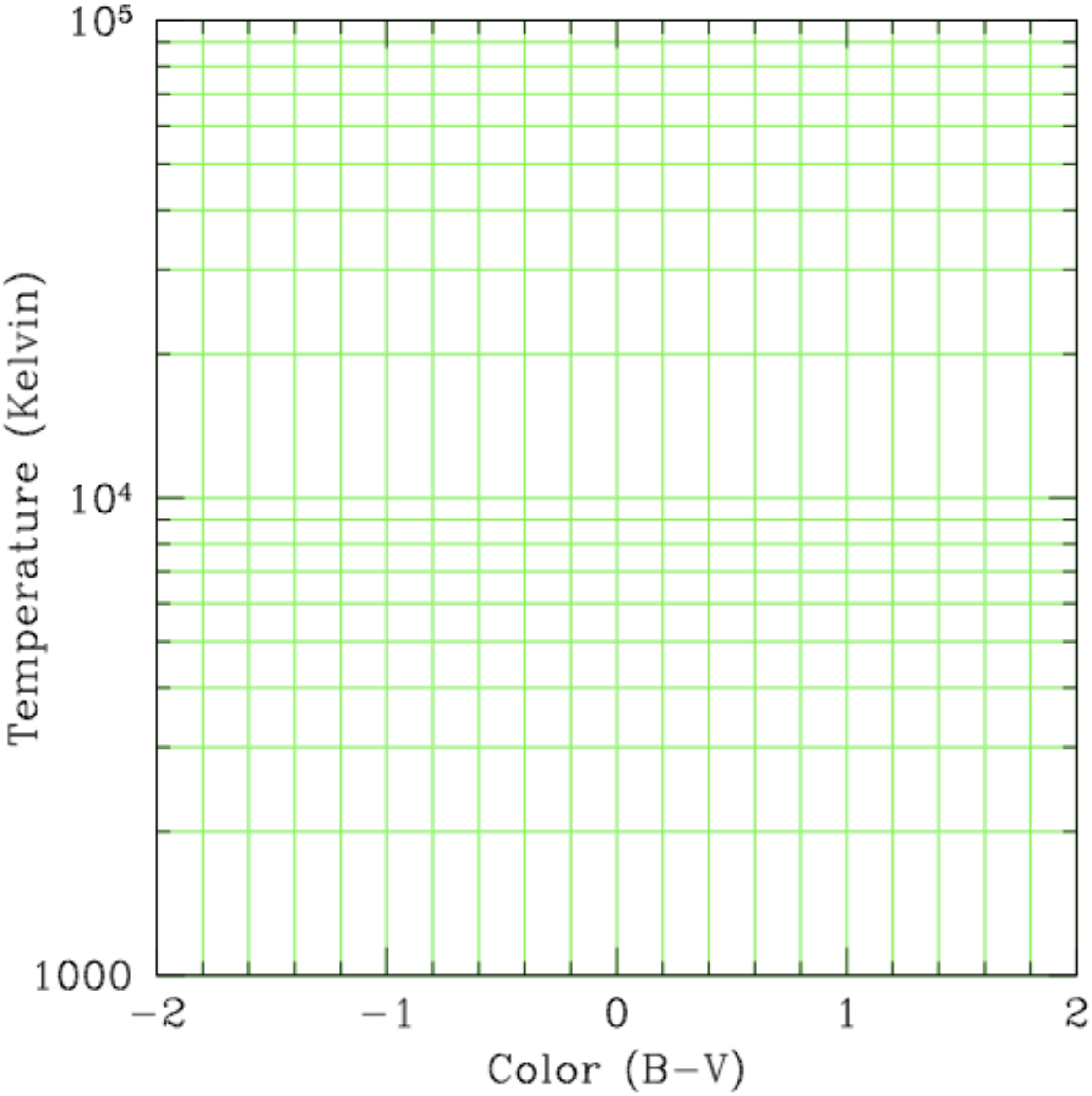
Spectral Type	Temp	Energy from photons in B filter	Energy from photons in V filter	$\frac{\text{Energy}_B}{\text{Energy}_V}$	$B-V$ $(=-2.5\log_{10}\frac{\text{Energy}_B}{\text{Energy}_V})$
O	40,000K				
B	15,000K				
A	10,000K				
F	7,500K				
G	6,000K				
K	4,500K				
M	3,000K				

2. The color you perceive an object to be depends on the ratio of light in different wave- length ranges. In the table above, divide the third column by the fourth column to calculate the ratio of the energy that passes through the B filter to the energy that passes through the V filter. Record your answer in the fifth column of the table (labeled “$\text{Energy}_B/\text{Energy}_V$”).

In the previous step, you probably found a nice sequence between the ratio of en- ergies in the B and V filters and the temperature of the stars. This number could potentially serve as the numerical value for “color” that you have been seeking. Unfor- tunately, due to the perversity of the ancient greeks, astronomers use “magnitudes” to record the energy that stars and galaxies emit. When comparing the energy received from a star in two different filters, they use a definition of “color” that is defined as $-2.5\log_{10}(\text{Energy}_B/\text{Energy}_V)$. They call this quantity “B – V ”, since it is equal to the apparent magnitude of a star when viewed in the B filter minus the apparent magnitude of a star when viewed in the V filter.

3. Using your answer for $\text{Energy}_B / \text{Energy}_V$ in the fifth column, calculate the astronomical color B – V . Record your answer in the sixth column.

4. On the plot below, make a graph of the B – V color versus the temperature of the star. Put a point for each star, then label the points and connect them with a line. Astronomers use similar plots to allow them to estimate the temperature of a star simply by measuring the apparent magnitude of a star in an image taken through a B filter and a V filter.

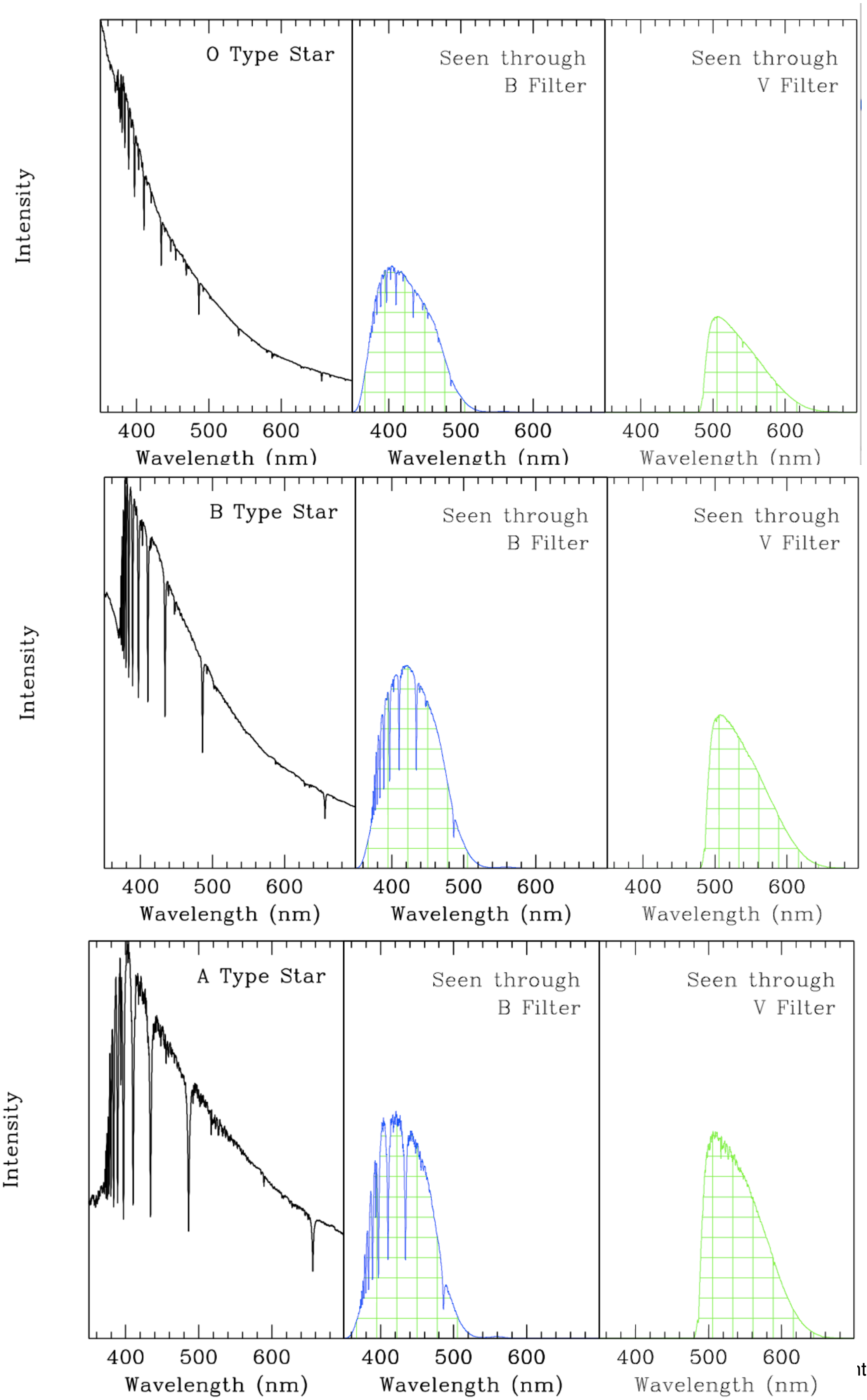


Final Questions

5. Suppose you measure a star with a B – V color of 0.2. Based on your graph, what spectral class would you expect this star to be? [O/B/A/F/G/K/M]

6. The presence of absorption lines makes the colors of stars different than the colors of the underlying thermal continuum. Many of the absorption lines are caused by elements heavier than Hydrogen or Helium in a star's atmosphere. If two G-type stars have identical temperatures, but have atmospheres that contain different amounts of these heavy elements (which astronomers call "metals"), would you expect the color of the stars to be the same, or different. Explain your reasoning.

Stellar Spectra



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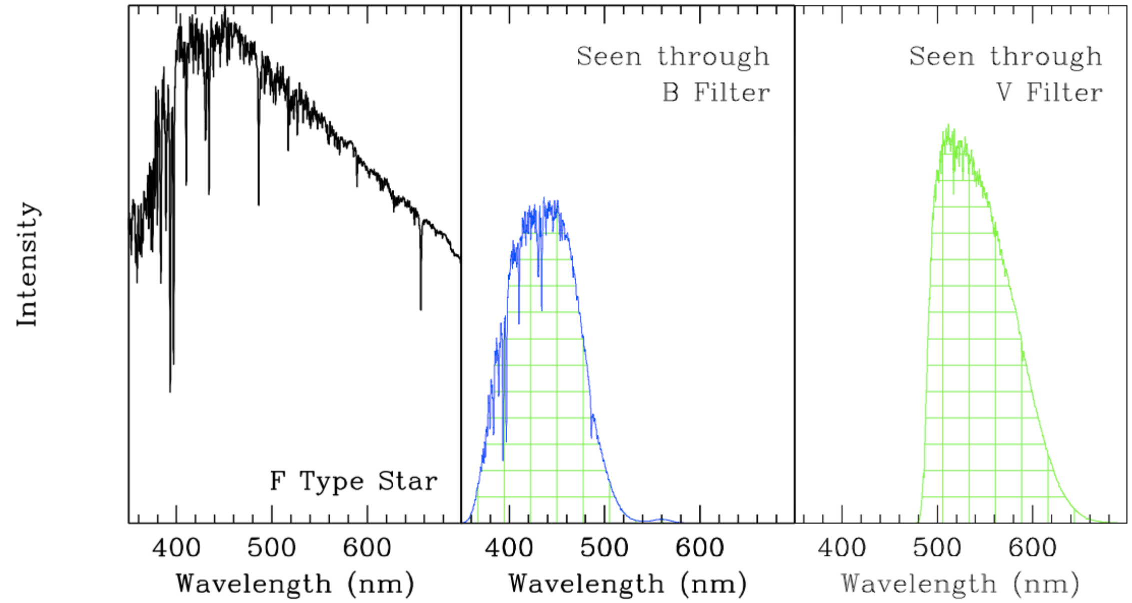
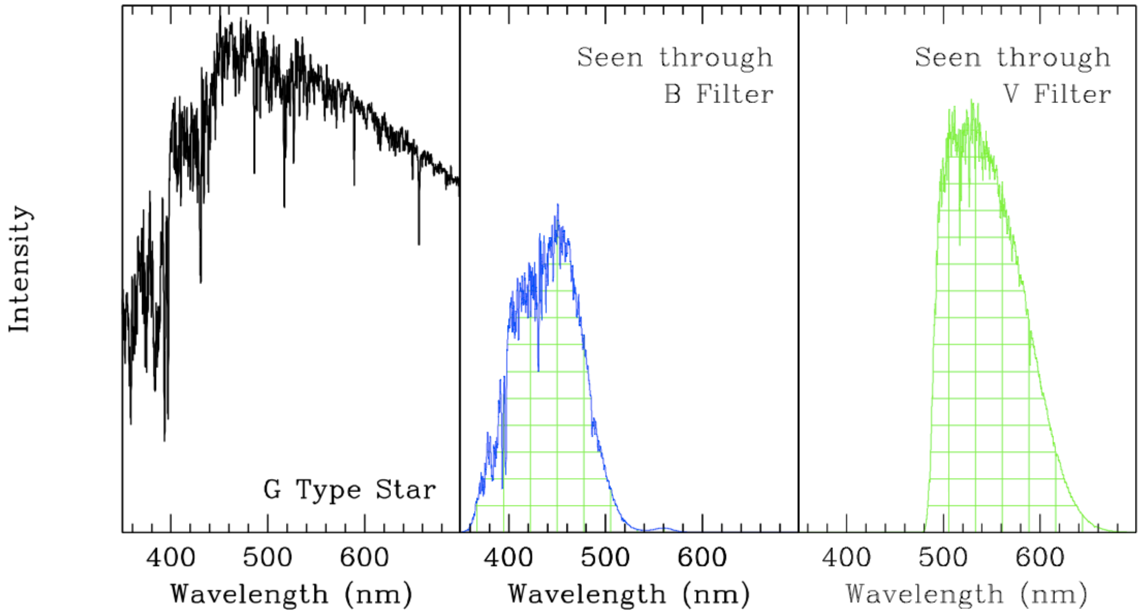
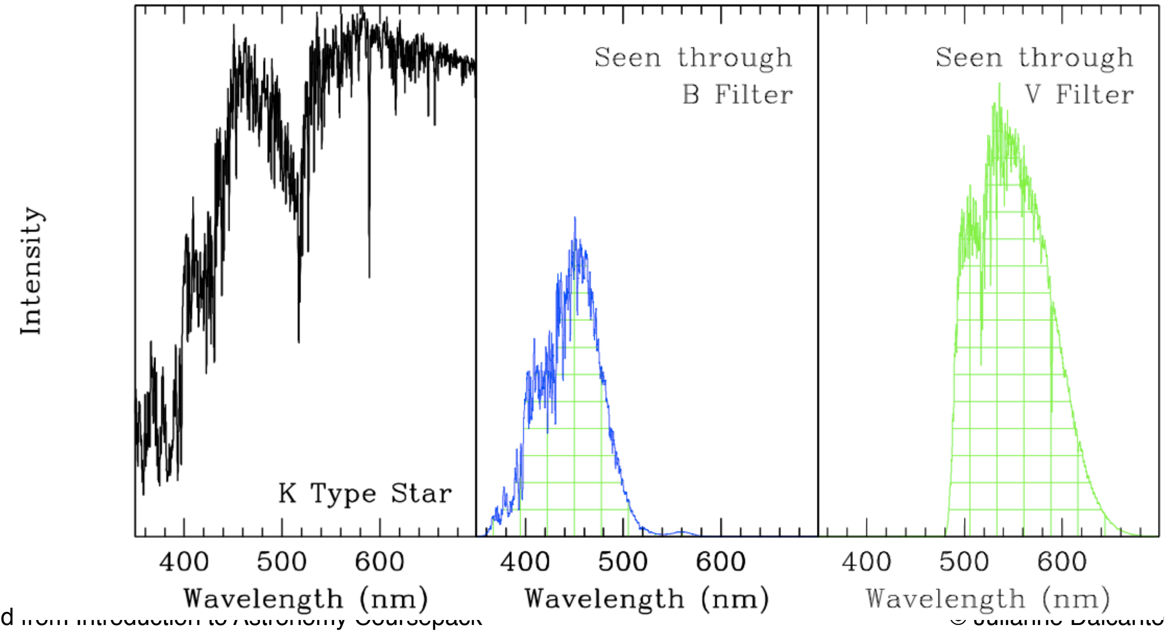
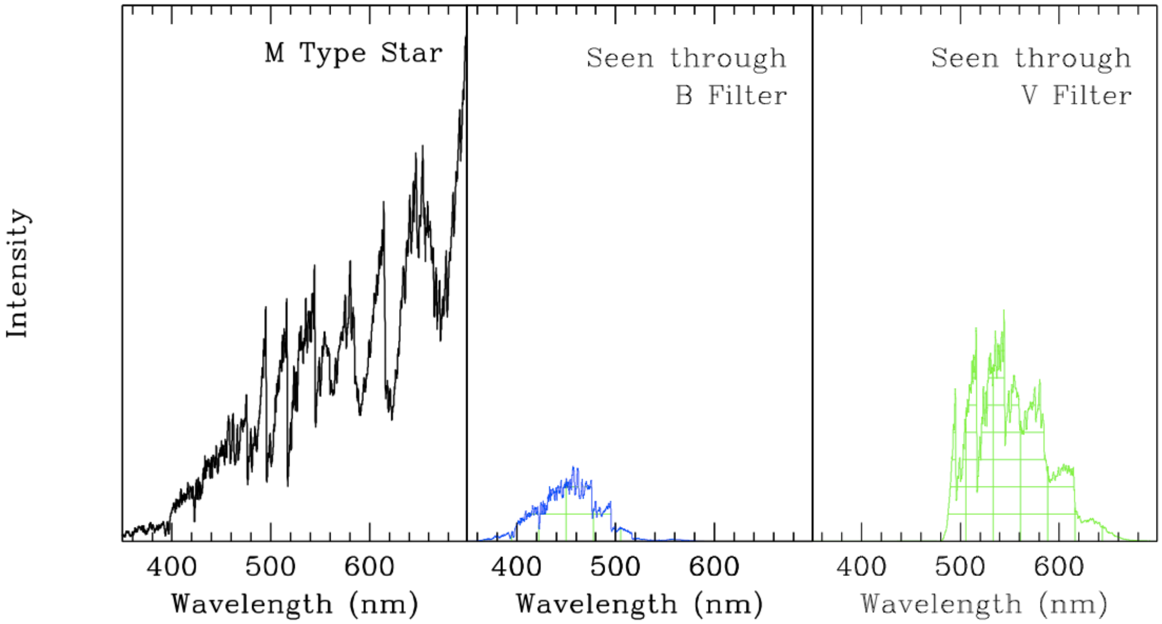

Intensity
F Type Star
Seen through
B Filter
Seen through
V Filter
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)


Intensity
G Type Star
Seen through
B Filter
Seen through
V Filter
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)


Intensity
K Type Star
Seen through
B Filter
Seen through
V Filter
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)


Intensity
M Type Star
Seen through
B Filter
Seen through
V Filter
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)
400
500
600
Wavelength (nm)