Project A:
The Spectral Classification of Stars

Why is Classification Important?

Classification lies at the foundation of nearly every science. In many natural sciences, one is faced with a bewildering degree of complexity in the subjects of one's study. However, by sorting objects into distinct classes, patterns and relationships can be revealed, suggesting an underlying order. For example, biologists have classified plants and animals into genus and species and through these classifications have discovered evolutionary connections among different life forms. Geologists likewise have an elaborate system of classification for rocks and minerals, which helps them to constrain the formation mechanisms for various materials. Astronomers are no exception. They classify planets as terrestrial or Jovian, galaxies as spiral, elliptical or irregular, and stars according to the appearance of their spectra.

In this exercise, you will study the method that astronomers use to classify stars by their spectra. The resulting classification was a key step in elucidating the underlying physics that produced stellar spectra. Thus, in astronomy as well as biology, the relatively mundane step of classification eventually yields the critical insights which lead to breakthroughs in understanding.

The Spectra of Stars

A spectrum of a star is produced by photons emitted from its very outermost layers. Photons emitted from further within the star interact frequently with the dense stellar material, and can not "escape" before being absorbed or redirected. Thus, we never see these inner photons, and only observe photons emitted from the star's more tenuous "atmosphere". This is similar to what would happen to someone trying to observe the Earth from outer space. They could never "see" below the ground, because the Earth was too dense, and could only observe light emitted in the atmosphere[1]. Technically, we say that the inner parts of a star (or the Earth) are "opaque", or "optically thick", and that only the atmosphere is "transparent" or "optically thin".

Almost all stellar spectra consist of a broad, smooth distribution of photons of different wavelengths, known as "continuum emission", with many absorption lines superimposed, changing the featureless smooth continuum spectrum into a much more complex one. The continuum emission is dominated by thermal radiation, which you have studied in class. Thermal radiation is produced by the interactions between the moving particles in a star's atmosphere and photons. The exact shape and amplitude of the thermal spectrum depends on the temperature of the star's atmosphere (i.e. how fast the particles in the atmosphere are moving).

While the spectrum of black body radiation is smooth, the actual spectrum of a star is much more complicated. Many absorption lines remove light from the underlying black body

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[1] Note that this is not an exact analogy, since the Earth is solid, and stars remain gaseous all the way to the center.

spectrum at specific wavelengths. These wavelengths depend on the exact ions, atoms, and molecules that exist in a star's atmophere, and thus the pattern of absorption lines reveals the chemical content and physical state of the star's atmosphere (e.g. are there many heavy elements in the star? is the atmosphere hot and mostly ionized, or cool and mostly molecular?). The absorption lines are produced when electrons in atoms and/or ions absorb individual photons from the smooth continuum that happen to have exactly the energy needed to boost a bound electron to a higher energy level. This removes light from the continuum, and leaves behind a dark region in the spectrum. These absorption lines are very narrow in wavelength, meaning they only remove photons at very specific wavelengths. However, sometimes there are so many absorption lines in a spectrum that it is difficult to see individual lines, and instead the spectrum has large jagged dark regions made from the superposition of many many different absorption lines from many different elements and ions. In some very cool stars (cooler than 3000 K), the absorption lines are produced by entire molecules absorbing photons, rather than electrons in atoms.

Why do Spectra of Stars Vary?

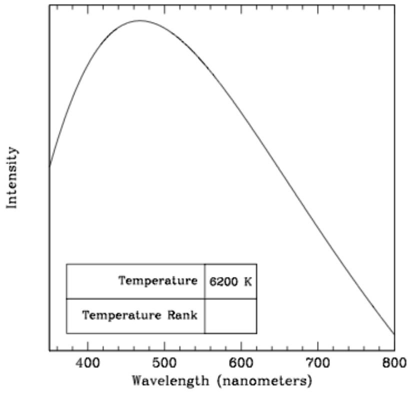
Stars come in a wide range of sizes and temperatures. The hottest stars in the sky have temperatures in excess of 40,000 K, whereas the coolest stars that we can detect optically have temperatures of only 1,000-1,500 K. The appearance of the spectrum of a star is very strongly dependent on its temperature. The temperature changes the shape of the underlying thermal continuum as well as the kinds of ions, atoms, and molecules which can exist in a star's atmosphere. For example, the very hottest stars (called O-type stars) show absorption lines due to ionized helium (He II) and doubly or even triply ionized carbon, oxygen or silicon. On the other hand, the coolest stars (M-, L-, and T-type) show lines produced by molecules like Titanium Oxide (TiO).

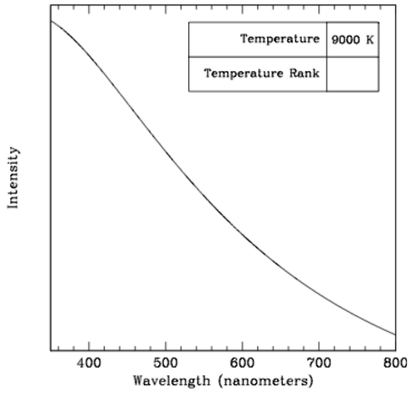
Procedure

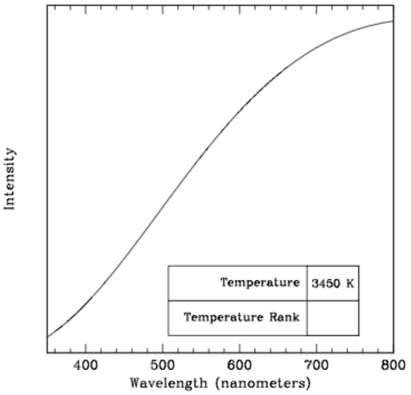
This project teaches the basic techniques and criteria of the Morgan-Keenan system of spectral classification. You will put several stars in a temperature sequence, first using the shape of the continuum, and then using the strength of the absorption lines. You will then use these observations to classify the stars.

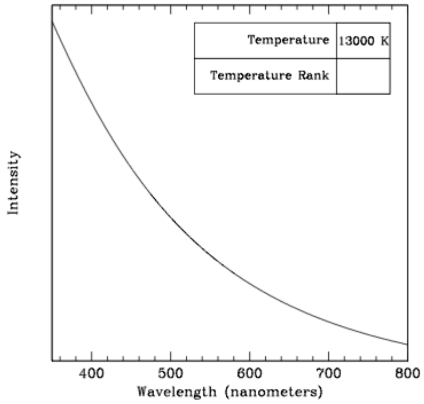
Estimating Temperature from the Shape of the Thermal Radiation Spectrum

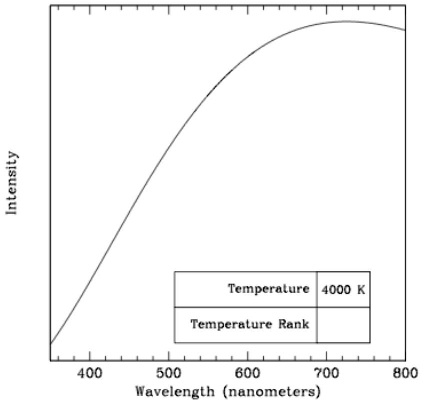
The plots below show how the spectra of objects of different temperatures would appear at optical wavelengths. Each curve shows a “thermal” or “black-body” radiation spectrum, for different temperatures.

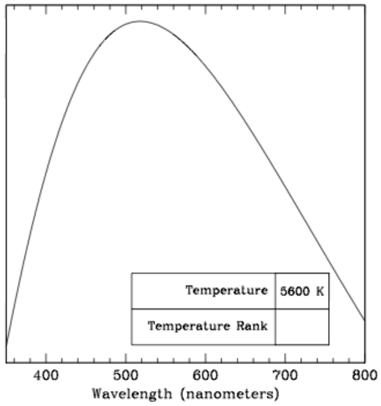












1. A thermal spectrum should always have a peak. Why don’t you see a peak in all of these plots?

2. Rank these spectra from hottest to coolest. Label the spectrum with the highest temperature with a “1”, the next hottest with a “2”, etc.

Stars, in order of decreasing temp						
Estimated temperature						

3. On the plots above, lightly shade under the thermal spectrum to indicate (1) all the light emitted blueward of 450 nanometers and (2) all the light emitted redward of 650 nanometers. Please use two different colors (for example, blue and red!) but do not shade in the boxes so that we can grade the previous problem!

4. Based on your shading, complete the following sentences:

a) A cool object emits more energy in _______ [red/blue] photons than in _________ [blue/red] photons, and will thus appear to be [red/blue] overall.

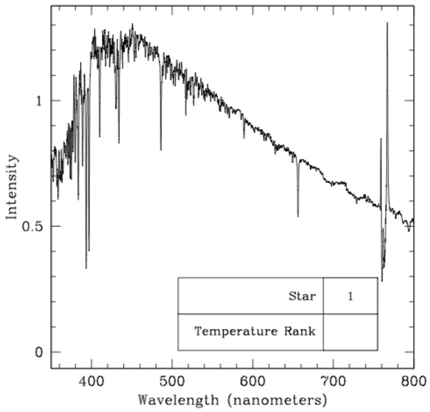
b) A hot object emits more energy in _________ [red/blue] photons than in [blue/red] photons, and will thus appear to be _________ [red/blue] overall.

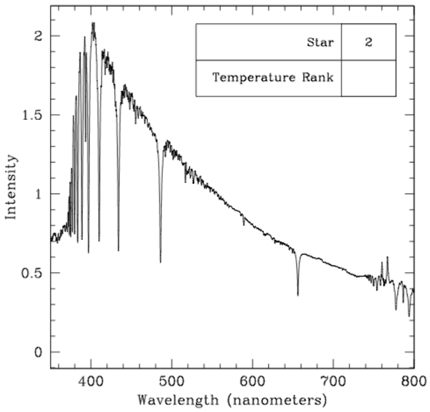
5. At roughly what temperature do you expect an object to appear yellowish, assuming it's emitting only thermal radiation? Briefly explain your reasoning.

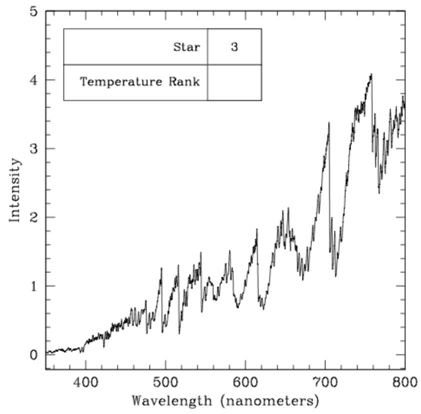
6. How does your answer for 5 compare to the temperature of the Sun?

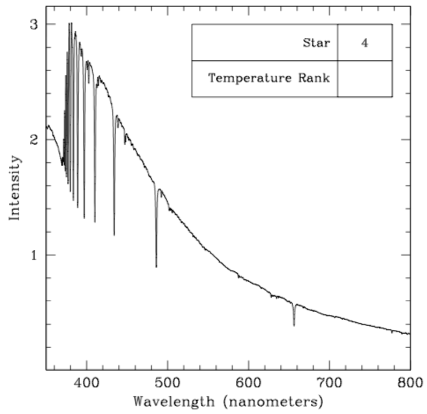
Estimating Stellar Temperature from the Shape of the Continuum

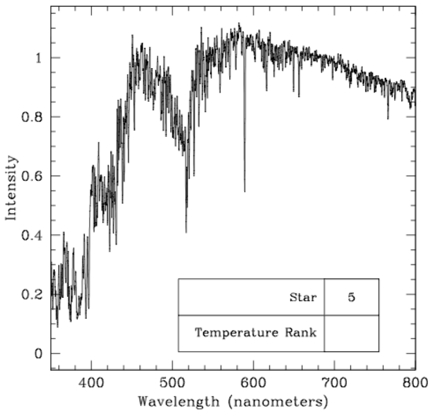
The plots below show spectra for actual stars. Although there are many complicated features in the spectra, their overall shapes follow thermal radiation spectra much like you saw on the previous page. Because these stars have different temperatures, the shape of the spectra vary substantially among the different stars.

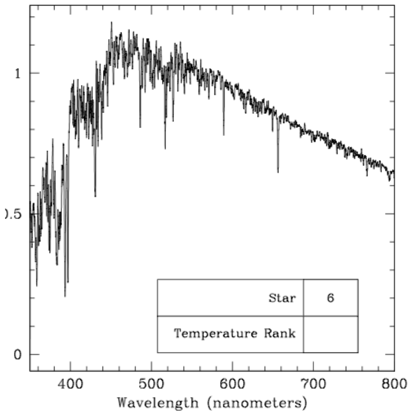












7. Based on your work in question 2, rank the stars from hottest to coolest. Label the spectrum with the highest temperature with a “1”, the next hottest with a “2”, etc.

8. Because you will need this information later in the project, in the table below record:
a) The temperature ranking from the previous question.

b) The approximate temperature of each star, estimated from the thermal spectra plotted on the previous page.

9. How does the temperature of the coolest star compare to that of a hot oven? [much hotter/a bit hotter/about the same/cooler]

Changes in temperature affect the state of matter. Since we only detect photons that are emitted from near the surface of a star, the temperature you measure for the star tells you something about what kind of material is at the star’s surface (i.e. in the star’s atomosphere).

10. Based on your answers above, do you expect that the surface of the star is made up of gas, liquid, or solid?

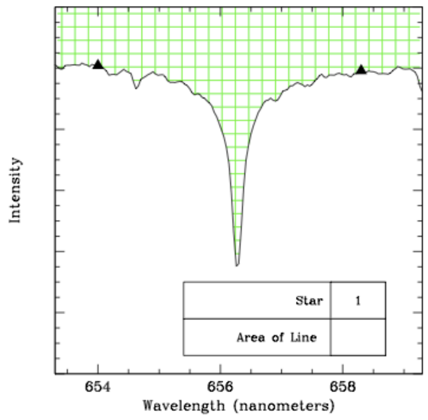
11. Which star do you think is most likely to be the most completely ionized near its surface?

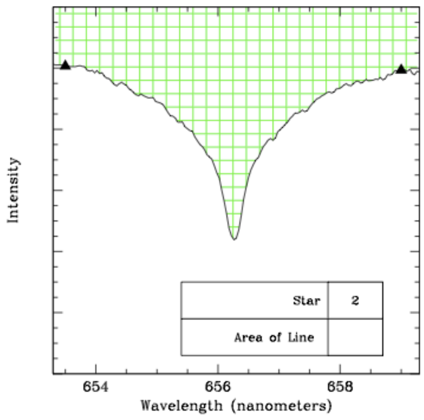
12. Which star do you think is most likely to have molecules in its atmosphere?

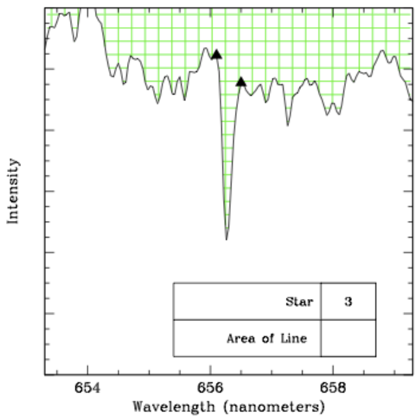
The Strength of Absorption Lines

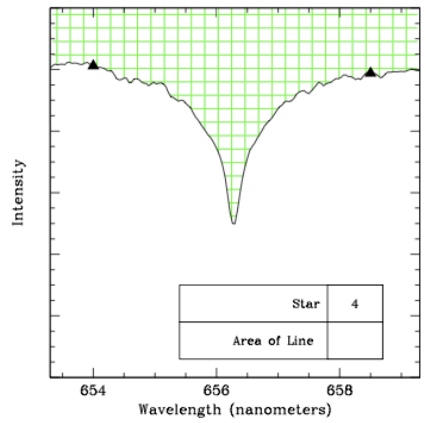
As you probably discovered, using the rough shape of a star's spectrum is not a particularly exact way to judge the star's temperature. Instead, astronomers use the strength of various absorption lines to diagnose the temperature of the star. Some of the most important of these lines are the "Balmer series" lines of Hydrogen, which you have learned about in class. The plots below are the same spectra from the previous page, but zoomed in to focus on the "Hα" line at 656.3 nanometers. You will now try to estimate the strength of this absorption line in the different stars.

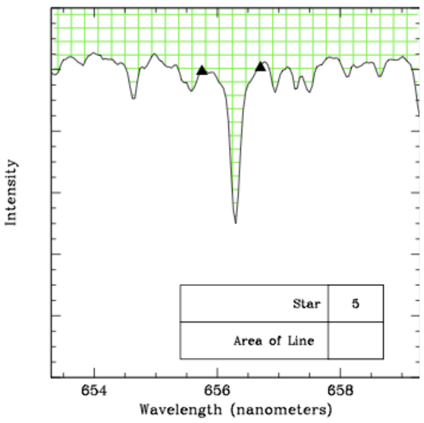
The first, and sometimes most challenging, step to figuring out how strong an absorption line is to estimate what the spectrum would have looked like without the line. If there were no absorption, the spectrum would look like the smooth thermal radiation spectra from earlier in this project. This smooth spectrum is called "continuum emission", since it is "continuous", lacking all those confusing bumps and wiggles caused by absorption lines. To estimate where the "continuum level" is, one usually tries to find regions of the spectrum that are near the absorption line, but that also seem to be free of absorption lines. One can use these uncontaminated regions to guess (or interpolate) the continuum.

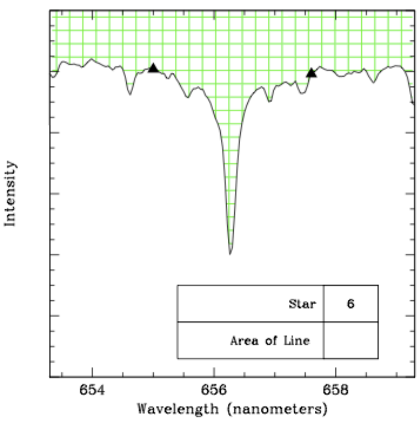












13. To help you estimate the continuum, there are two dark triangles on each of the plots above. These triangles were selected to be in relatively uncontaminated parts of the spectrum. Connect each pair of triangles with a straight line to estimate the continuum level.

Now that you have estimated what the spectrum would look like without the absorption line, you now can estimate the strength of the absorption lines by measuring their areas. The "area" of the line is a measure of how many Hα photons were absorbed by a star's atmosphere, which will be proportional to the number of atoms capable of producing the Hα absorption line.

14. Measure the area of the Hα absorption line by using the grids on the images to count all the boxes that fall between your estimate of the continuum level and the actual spectrum. Try your best to account for partial boxes, particularly for the weaker lines. Record your answer in the space provided on the plot.

The strength of hydrogen absorption lines was a key component of the initial classification of stars. Williamina Fleming classified thousands of stars on the basis of their hydrogen lines, labelling the ones with the strongest lines "A", the second strongest lines "B", and so on down to "O", for the stars with the weakest hydrogen absorption lines in their spectra.

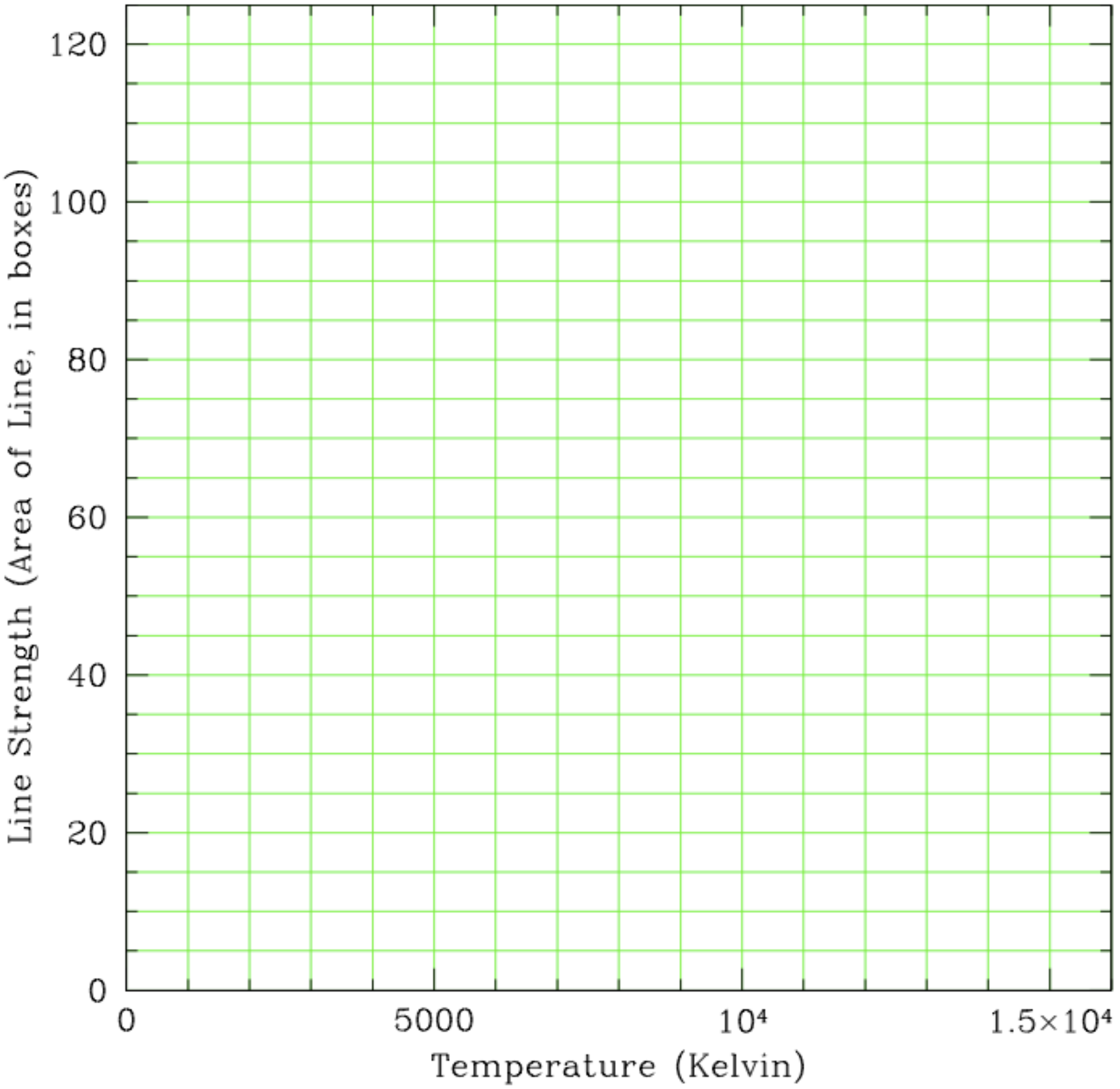
15. The table below shows the potential stellar classifications (BAFGKM) that can be applied to the stellar spectra you have been looking at in the project. When these stars are sorted in order of line strength, they should reproduce the alphabetic order of Williamina Fleming's original classification based on the prominence of the Hydrogen lines (ABFGKM).

However, when they are sorted by temperature, they should reproduce the temperature sequence discovered by Annie Jump Cannon (BAFGKM). In the table below:

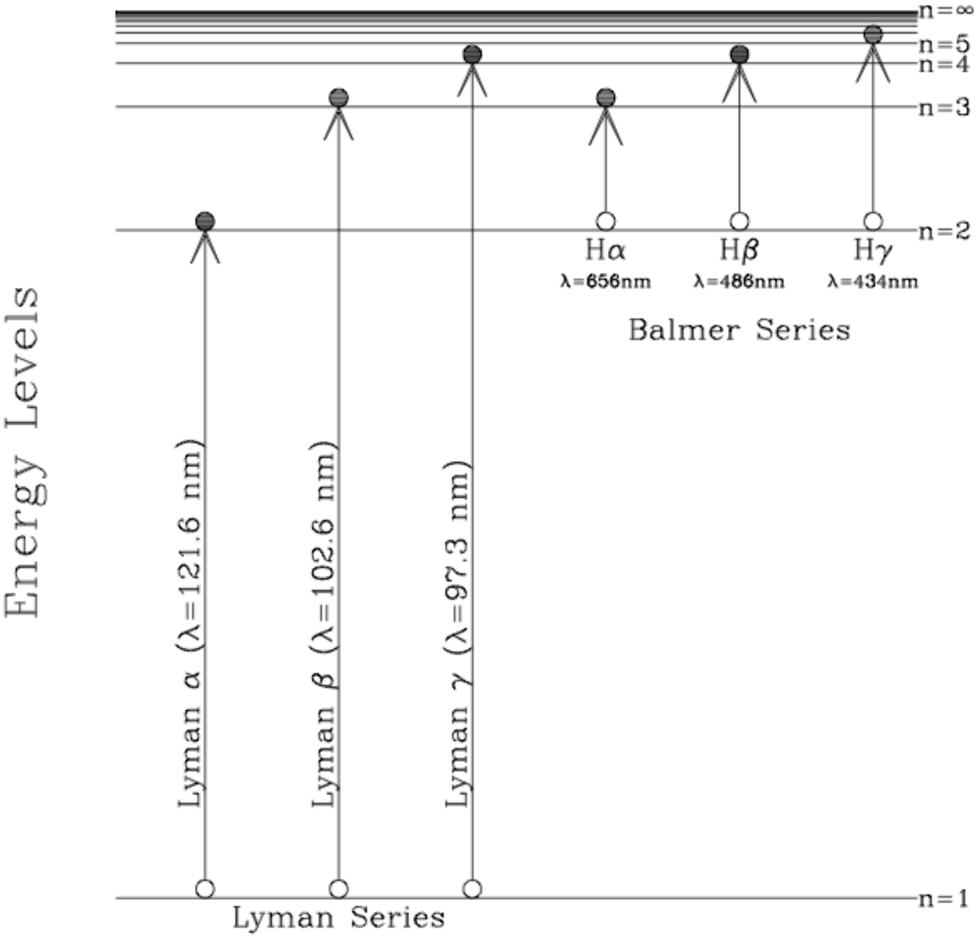
a) Rank the stars from the strongest to the weakest hydrogen lines, and record your answer in the second row. Use the number of the star on the plot to refer to a specific spectrum.
b) Record the area of the line in the third row (i.e. copy your results from the individual plots of the Hα line)
c) Record the temperature that you estimated for each star from the previous table.

Classification	A	B	F	G	K	M
Stars, in order of decreasing line area						
Area of absorption line						
Estimated temperature						

16. On the graph below, plot temperature versus "line strength" (as measured by the area of the absorption line) for all the stars in your table. Label your plotted points with the letter designation from the table (i.e. Put a letter "A" next to the point for the star with the largest area).



17. In class you learned about the Balmer series. Below is the energy level diagram showing the three lowest energy Balmer series transitions and their wavelengths.



a) Returning to the spectrum of the star you classified as an A star (i.e. the plots between questions 6 and 7), label the absorption lines due to the Hα, Hβ, and Hγ transitions.

b) Explain why cool stars show weak Hα lines?

c) Explain why the very hottest stars show weak Hα lines as well.