

Stellar Spectroscopy

The Message of Starlight



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Teaching Notes

A Note From The Author

The goal of this activity is to learn how to classify stars by studying their spectra. It was originally intended as an instructional tool to introduce the concepts of spectroscopy necessary for the RBSE “Variable Stars” and “AGN Spectroscopy” research projects, but it is also useful as a standalone tool to teach spectroscopy in general.

Please note that it is assumed that the instructor and students are familiar with the concepts of spectroscopy as it is used in astronomy, as well as stellar classification and evolution. Some information are missing for these topics, potentially resulting in confused teachers and/or students. If you are having a particular problem, please don’t hesitate to contact me.

Prerequisites


To get the most out of this activity, students should have a basic understanding of the following concepts:

- Spectroscopy in astronomy
- Stellar evolution
- Stellar classification

Description of the data

The spectra used in this activity were obtained with the 2.1-meter telescope and its “GoldCam” optical spectrograph at Kitt Peak National Observatory. The spectra cover most, if not all, of the optical spectrum (what we can see with our eyes). The names of the known stars give some information about their origin. For example, most of the stars are from the Henry Draper catalog of bright stars, and are given an “hd” prefix. The names of some of the other stars indicate their location; e.g., “EQ Peg” is located in the constellation of Pegasus. Spectra of the Messier objects M74, a globular cluster, and M76, the “Little Dumbbell” Nebula, are also included as examples. Note that this is *real* data, not a simulation.

About the software

This exercise is designed for Graphical Analysis by Vernier Software (versions 3.1 or later). An “” icon appears when analysis of the data with the computer is necessary. This manual uses images from the Macintosh version of Graphical Analysis to illustrate the examples, but the Windows version is essentially



The 2.1-meter telescope at Kitt Peak National Observatory in Arizona.



The actual 2.1-meter telescope. The white spot on the dome (to the left) is used to calibrate the spectrograph.



The “GoldCam” spectrograph, attached to the bottom of the 2.1-meter telescope.

identical. To order Graphical Analysis, Vernier Software can be reached at the following address:

Vernier Software, Inc.
8565 S.W. Beaverton-Hillsdale Hwy.
Portland, Oregon 97225-2429
Phone: (503) 297-5317, Fax: (503) 297-1760
email: dvernier@vernier.com
WWW: <http://www.vernier.com/>

Summary of Commands

File/Open... (⌘-O)

Opens the spectrum. Use this command if the spectrum file is in GA 3.1 format. Unfortunately GA 3.1 is unable to open files in GA 2.0 format.

File/Import from Text File...

Use this command to load a spectrum that is in text format. For this command to work properly the spectral data must be comma-delimited.

File/Close

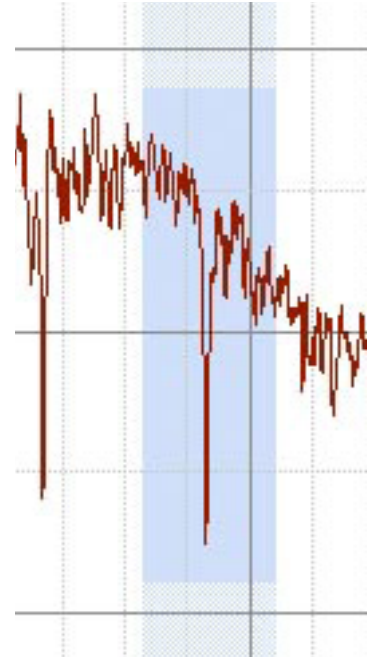
Use this command to close the current spectrum.

Analyze/Examine (⌘-E)

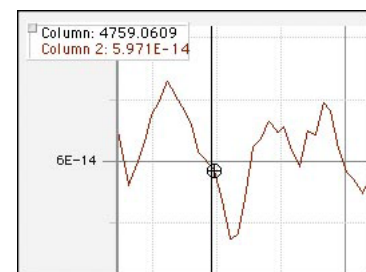
Activates the examine tool (the magnifying glass) which gives the wavelength (the X value) and the flux per unit wavelength (the Y value) of the datapoint closest to the cursor.

Options/Graph Options...

Under the “axes options” window, the X- and Y-axes can be rescaled either by inputting ranges manually or automatically by using the data values.



To zoom in on a portion of the spectrum click and drag a rectangle around a region and then select **Zoom Graph In** from the **Analyze** menu.



Use the examine tool (using **Analyze/Examine** or ⌘-E) to determine the wavelength (the X value) of absorption and emission lines in the spectrum. In this example the wavelength of the datapoint in the same column as the cursor is 4759 Angstroms (Å). The flux density per unit wavelength (the Y value) is 5.971×10^{-14} erg cm⁻² s⁻¹ Å⁻¹.

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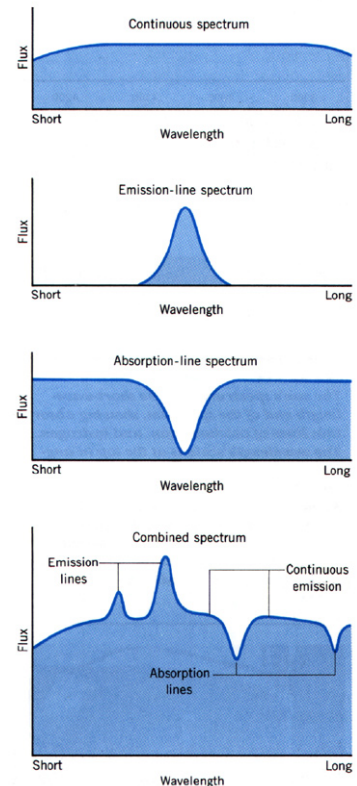


Introduction

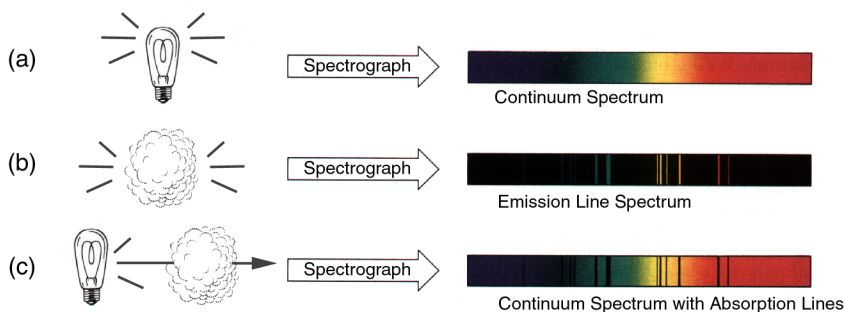
The power of spectroscopy

Spectroscopy is the study of “what kinds” of light we see from an object. It is a measure of the quantity of each color of light (or more specifically, the amount of each wavelength of light). It is a powerful tool in astronomy. In fact, most of what we know in astronomy is a result of spectroscopy: it can reveal the temperature, velocity and composition of an object as well as be used to infer mass, distance and many other pieces of information. Spectroscopy is done at all wavelengths of the electromagnetic spectrum, from radio waves to gamma rays; but here we will focus on optical light.

The three types of spectra are shown in the diagram below: continuous, emission line and absorption line. A continuous spectrum includes all wavelengths of light; i.e., it shows all the colors of the rainbow (case “a” in the diagram below). It is produced by a dense object that is hot, either a dense gas (such as the interior of a star) or a liquid or solid (e.g., a tungsten filament in a light bulb). In contrast, an emission line spectrum consists of light at only a few wavelengths, i.e., at only a few discrete colors (case “b”). An emission line spectrum can only be produced by a hot, tenuous (low-density) gas. Importantly, the wavelengths of the emission lines depend on the *type* of gas; e.g., Hydrogen gas produces different emission lines than Helium. Absorption lines can be best thought of as the opposite of emission lines. While an emission line adds light of a particular wavelength, an absorption line subtracts light of a particular wavelength. Again opposite of emission lines, absorption lines are produced by a *cool* gas. Naturally there must be some light to subtract, so absorption lines can only be seen when superimposed onto a continuum spectrum. Thus, for absorption lines to be seen, cool gas must lie between the viewer and a hot source (case “c”). The cool gas absorbs light from the hot source before it gets to the viewer. Here “hot” and “cool” are relative terms- the gas must simply be cooler than the continuum source. Also note that a gas absorbs the same wavelengths of light that it emits.



Astronomers like to plot spectra differently than you often see in a textbook. Spectra are plotted as flux (the amount of light) as a function of wavelength. In the diagram above the three types of spectra are shown. In the bottom frame they are shown together, as they might appear in an object’s spectrum.

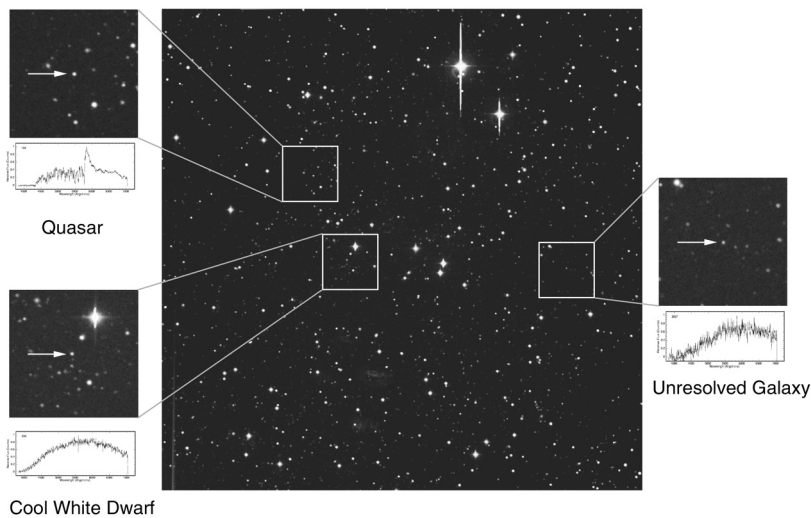


Emission and absorption lines are named after the element responsible for the line (remember that different types of gas produce different lines) and the gas’ ionization state. If a gas is heated hot enough its atoms will begin to lose their electrons, either by absorbing photons (particles of light) or by collisions with

other particles. When an atom loses one or more of its electrons it is *ionized*. Losing electrons changes the wavelengths of the emission and absorption lines produced by the atom, thus it is important to know its ionization state. A roman numeral suffix indicates the ionization state, where higher numbers indicate higher ionization states; e.g., “Na I” is neutral (non-ionized) Sodium, “Ca II” is singly-ionized Calcium, etc. In general hotter gases are more highly ionized. Some common lines have special names for historical reasons. Because Hydrogen is by far the most common element in the Universe, many of its lines were given special names; e.g., “Ly α ” is a very strong ultraviolet line which is produced by neutral hydrogen (H I); it is part of the *Lyman* series of Hydrogen lines. “H α ”, “H β ”, “H γ ”, etc. are strong optical lines, also produced by neutral Hydrogen, and are part of the *Balmer* series.

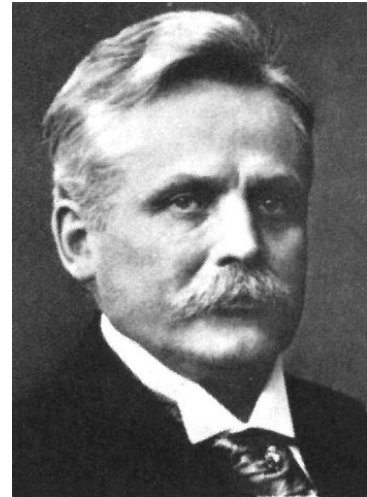
Spectroscopy as an Identification Tool

When looking up at the night sky with thousands of stars overhead it is easy to wonder: How do astronomers know what they are?



Nomenclature:

“Na I” is pronounced “sodium one”, “N II” is pronounced “nitrogen two” and “H α ” is pronounced “H alpha” or “hydrogen alpha”, etc.



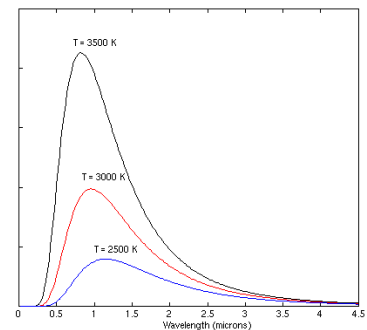
Wilhelm Wien
(1864-1928)

For example, in the image above there are hundreds of points of light. Most are stars within our galaxy, but this image alone doesn’t tell us much. How then do astronomers know so much about stars? Often the answer is spectroscopy. In this project, you will study the spectra from a wide range of different types of stars. By analyzing the spectra you will be able to classify each star.

The Continuum Spectrum and Wien’s Law

Stars can simply be thought of as hot balls of gas in space. Their interiors are very hot and dense; and they have an outer layer of cooler, low-density gas, which is known as the star’s *atmosphere*. Because the interior of a star is dense it produces a continuous spectrum, which is known as a *blackbody continuum*.

The spectral shape of a blackbody continuum depends on the temperature of the object. Interestingly, the shape of the continuum is *not* dependent on the star’s composition. The spectra of hot stars (>10,000 K) peak at blue wavelengths, giving them a bluish color. The spectra of cool stars (< 4000 K) peak at red wavelengths, giving them a reddish color. Stars like the sun (~6000 K) peak at yellow wavelengths, giving them a yellowish to white color. Cooler objects, such as planets and people, also produce a blackbody continuum, but due to



Example spectra for three blackbody spectra, at temperatures of 3500, 3000 and 2000K respectively. Note that the peak of the spectrum for the hotter objects occur at shorter wavelengths.

their lower temperatures (~300 K) the peak of their spectral continuum is in the infrared. The relationship between an object's temperature and the peak of its spectrum is given by Wien's Law:

$$T = \frac{2.897 \times 10^7 \text{ K } \text{\AA}}{\lambda_{max}}$$

Where T is the temperature of the object in Kelvin and λ_{max} is the peak wavelength of the continuum, measured in Angstroms (\AA).

Spectral Absorption and Emission Lines

A star's continuum spectrum is useful for determining the temperature of the surface of the star, but most of what is known about stars is determined from the many spectral lines seen in their spectrum.

A close inspection of a star's spectrum will reveal many absorption lines, and for some stars, emission lines as well. These spectral lines can be used to determine an incredible amount of information about the star, including its temperature, composition, size, velocity and age, as well as many other properties. Most of what we know about stars has been determined by the study of their spectral lines.

Spectral Classification

At the end of the 19th century astronomy underwent a revolution with the invention of the objective prism and photographic plates. For the first time astronomers were able to record and analyze the spectra of stars. Spectroscopy revealed that stars show a wide range of different types of spectra, but at the time it was not known why. Astronomers at the Harvard College Observatory obtained spectra for over 20,000 stars in hopes of understanding how each star was related to the others. They developed a scheme in which each star was classified based upon the strength of the Hydrogen absorption lines in its spectrum. *A* class stars were those stars which had the strongest Hydrogen absorption lines; *B* class stars had slightly weaker lines, etc. Originally the classification scheme went from *A* to *Q*, but over time some of the stars were reclassified and some categories were removed. Through the work of Indian astronomer Meghnad Saha and others it was realized that a primary difference between stars was their temperature, and so the classification scheme was reorganized into "OBAFGKM" based upon temperature, from the hot *O* stars to the cool *M* stars. Several mnemonics have been created to remember this confusing sequence, a good one is, "Only Bad Astronomers Forget Generally Known Mnemonics". The primary goal of this exercise is to use the spectrum of each star to determine its spectral class, which is described below.

Absorption and emission lines are produced by a star's atmosphere and outer layers. This gas is too low a density to produce a continuum spectrum. What types of spectral lines you see strongly depend on the star's temperature. Helium is very difficult to ionize, so spectral lines by ionized Helium (He II) appear in only the hottest stars, the *O* stars. *B* stars are hot enough to energize their Helium, but are not hot enough to ionize it. Thus *B* stars have He I lines but do not have He II lines, and *A* stars do not have any Helium lines at all.

In very hot stars (> 10,000 K) most of the Hydrogen gas in the star's atmosphere will be ionized. Since an ionized Hydrogen atom has no electron it cannot produce any spectral lines, thus the Hydrogen lines are weak in *O* stars. *B*, *A*, and *F* stars

Nomenclature:

Astronomers use the Greek letter "λ" (pronounced "lambda") as a symbol for wavelength. Wavelengths are measured in units of *Angstroms*, or "Å" for short. $1\text{\AA} = 10^{-10} \text{ m} = 0.1 \text{ nm}$.



Annie Jump Cannon was one of several women who developed the stellar classification scheme at Harvard College Observatory.

Nomenclature:

Astronomers refer to any element other than Hydrogen and Helium as "metals.."

are within the right range of temperatures to energize their Hydrogen gas without ionizing it. Thus the Hydrogen “Balmer” lines are very strong in these stars. At lower temperatures the Hydrogen gas isn’t as easily excited, thus the Balmer lines aren’t as strong in *G* and *K* stars, and are barely present in *M* stars.

Metals are easier to ionize than Hydrogen and Helium and therefore don’t require as high of temperatures, thus spectral lines from ionized metals (e.g., Fe II, Mg II, etc.) are common in stars of moderate temperatures (roughly 5000 to 9000 K). Metals produce many more spectral lines than Hydrogen and Helium because they have more electrons. In general the cooler the star the more metal lines it will have. CaII $\lambda\lambda 3933, 3968$ (known as the “Calcium H and K” lines) is a particularly strong set of lines seen in cooler stars. In *F* stars and cooler the CaII lines are stronger than the Balmer lines. In the cool *G* and *K* stars lines from ionized metals are less abundant and lines from neutral metals are more common. In the very cool *M* stars, their atmospheres are cool enough to have molecules which produce wide absorption “bands”, which are much wider than the atomic spectral lines discussed above. These absorption bands radically alter the shape of the continuum, to the point where it is not even clear what the continuum really looks like. The table below characterizes the spectral properties of the different classes:

Class	Spectral Lines
O	Weak neutral and ionized Helium, weak Hydrogen, a relatively smooth continuum with very few absorption lines
B	Weak neutral Helium, stronger Hydrogen, an otherwise relatively smooth continuum
A	No Helium, very strong Hydrogen, weak CaII, the continuum is less smooth because of weak ionized metal lines
F	Strong Hydrogen, strong CaII, weak NaI, G-band, the continuum is rougher because of many ionized metal lines
G	Weaker Hydrogen, strong CaII, stronger NaI, many ionized and neutral metals, G-band is present
K	Very weak Hydrogen, strong CaII, strong NaI, and many metals, G-band is present
M	Strong TiO molecular bands, strongest NaI, weak CaII, very weak Hydrogen absorption, (Note: Hydrogen may be <i>emission</i> lines.)

Note that the “strength” of a line is a measure of how much light is absorbed by the line (i.e., how big of a dip it is). A strong line will absorb as much as 25% or more of the flux. Weaker lines will absorb less. The strength of a line is easy to estimate: Measure the flux density at the lowest point of the absorption line (f_{line}). And estimate the flux density of the continuum level (f_{cont}) at a point just outside of the line. The strength of the line is given by:

$$\text{Strength} = 1 - \frac{f_{line}}{f_{cont}}$$

The strengths of the lines listed in the table above are relative to the different classes. For example, The hydrogen lines are present but relatively weak in O class stars. They become stronger in class B, and are strongest in class A and F stars. They become weaker in G stars and weakest by K class. In M stars hydrogen lines will either appear as very weak absorption or occasionally as emission lines (if the star is flaring).

Because there is a continuous range of temperatures among stars the classes have 10 subdivisions, with larger numbers having lower temperatures. For example, an *A0* star lies at the hot end of the *A* class, with a temperature of 9500 K, while *A9* is at the cool end near 7000 K. An *A9* star is therefore more like an *F0* star than an *A0* even though an *A9* and *F0* are technically different classes.

Spectral Class Characteristics:

Class	Color	Temperature (K)
O	Blue	> 30,000
B	Blue-White	9500-30,000
A	White	7000-9500
F	Yellow-White	6000-7000
G	Yellow	5200-6000
K	Orange	3900-5200
M	Red	< 3900

Bright Stars in Each Class:

Class	Examples
O	Naos
B	Anilam
A	Sirius, Vega
F	Canopus, Polaris
G	The Sun, Capella
K	Arcturus, Aldebaran
M	Betelgeuse

Hint:

The most important spectral lines to look for are the hydrogen (“Balmer”) lines, the CaII 3933,3968 lines, the NaI 5893 line, and the “G-band” 4300 line.

Note!

The cooler the star, the more metal lines present. Thus, the overall spectrum for hot (OBA) stars is relatively smooth (except for the hydrogen lines). The spectrum for cooler (FGK) stars becomes more distorted by metal lines the cooler the star. The M stars have spectra so dominated by TiO molecular bands and metal lines that no continuum is visible.

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Procedure

For each spectrum you will analyze the continuum, absorption lines and emission lines (if present). To better learn how to analyze a star you are encouraged to first work through the example.

Determining the Temperature from the Continuum

First you will study the continuum of each star to determine its temperature. You will use the examine tool to estimate the peak wavelength for the continuum of each star as best as you can. Note that this is not necessarily the highest datapoint in the spectrum, as emission and absorption lines are also present. Determining the peak of the continuum is not easy for stars with many absorption lines because the lines can significantly alter the shape of the continuum, so do the best you can.

To measure the location of the continuum peak in the spectrum do the following:

- ☐ Open the spectrum and measure the peak of the continuum:
 - **File/Open...** (⌘-O) the spectrum to be studied.
 - If the graph shows only a bunch of dots make sure the graph options are set correctly. To do this select the graph by clicking on it once and then selecting **Options/Graph Options...** from the menu. Make certain the “connect lines” option is selected.
 - Activate the examine tool (**Analyze/Examine** or ⌘-E). The information box gives the wavelength (the X value) and flux per wavelength (the Y value) of the datapoint in the same column the cursor. Position the cursor over the region you which you think is the peak of the spectrum and record its wavelength (the X value).

For some of these stars, the peak of their continuum spectrum occurs outside of the limits of the spectrum (off the left or right side). For these objects our spectrum is insufficient to determine the peak of the continuum.

1. For each star for which you can see the peak in the continuum spectrum, use Wien’s Law to calculate its temperature.
2. Sort the stars based upon their temperature, from the coolest to the hottest. For the objects for which the spectrum is insufficient to see the peak of the spectrum just give it your best guess; later you will use other diagnostics to determine which stars are hotter than the others.

Absorption and Emission Lines

Now you will measure the wavelength of the absorption lines in each star to identify the spectral class of the star. Some stars have emission lines as well, and the wavelengths of these lines should be measured too.

☐ Measure the positions of strong spectral lines:

- Use the examine tool (**Analyze/Examine** or $\frac{\text{H}}{\text{E}}-\text{E}$) to measure the wavelengths of at least four of the strongest absorption and/or emission lines in the spectrum of each star. Identify these lines with the table of common spectral lines given to the right.

A few notes: This is not a complete list of all the spectral lines seen in these stars. Most of the lines given are between 4000 and 5000Å, because historically this is the portion of the spectrum astronomers have studied most closely. Also note that some lines overlap, e.g., H ϵ and CaII λ 3968. The molecular bands can be quite wide, 50Å or more. For the molecular bands you should estimate the location of the center of the band and measure its wavelength as best as you can.

The goal is not to identify each and every absorption line in the spectrum, but rather to gain enough information to identify the class of star; e.g., only the hottest stars have helium lines, so the presence of several of the helium lines is an important indicator. Similarly, metal lines are stronger in the cooler stars. If an observed line has a wavelength that is close to two lines in the table, you may be able to differentiate by studying other lines. For example, if you see an absorption line at 3970 it could be either H ϵ and CaII λ 3968. If you see the other hydrogen Balmer lines it is likely H ϵ . If you see the other CaII line at λ 3933 it is likely CaII λ 3968. If you see CaII and Hydrogen lines it is likely a blend of both lines.

Note that stars these stars are moving slowly, such that their spectra will not be noticeably red or blueshifted. Their spectral lines should therefore appear roughly in the positions listed in the table. Because this is real data there is some error in measuring the wavelength, although your measured positions should match the values in the table to within about 3Å.

The Earth's atmosphere causes strong absorption features which are known as *telluric* absorption lines, which are also listed in the table. Sodium in the Earth's atmosphere also tends to cause the NaI absorption line to appear at 5890Å.

3. Based upon the emission and absorption lines you identified and the information in the classification table, assign a spectral class to each star. For each star describe upon what evidence you have based your decision, and how confident you are in your classification (e.g., how certain are you a star is a *B* star and not an *A* star?)
4. Using your results from question #3 again list the stars from coolest to hottest. How well does this agree with the list you generated based upon the continuum and Wien's Law?
5. These are real stars and, like people, each star is special and unique in its own ways. Some of these stars have characteristics which make them deviate from the classifications given. For the stars which deviate describe how they do not match the description of their spectral class. Do any of the stars not match *any* of the spectral classes?
6. *Advanced:* We know that the absorption lines in a star's spectrum are caused by its cooler atmosphere, but some of these stars also have emission lines. Describe a physical scenario in which a star's spectrum will contain emission lines. Note that it doesn't have to be the right explanation for the stars in question here.
7. Why should astronomers have all the fun? Create your own mnemonic for the spectral classification sequence.

Common Spectral Lines (given in Å):

Hydrogen (the "Balmer Series"):

H α	6563
H β	4861
H γ	4340
H δ	4101
H ϵ	3970
H8	3889
H9	3835
H10	3798
H11	3771
H12	3750

Helium:

He I	4026, 4388, 4471, 4713, 5015, 5048, 5875, 6678
He II	4339, 4542, 4686, 5412

Metals:

Ca II	3933, 3968
C II	4267
C III	4649, 5696
C IV	4658, 5805
N III	4097, 4634
N IV	4058, 7100
N V	4605
O V	5592
Na I	5893
Mg I	5167, 5173, 5183
Mg II	4481
Si III	4552
Si IV	4089
Ca I	4226
Sc II	4246
Ti II	4444
Mn I	4032
Fe I	4045, 4325
Fe II	4175, 4233
Sr II	4077, 4215
Hg	4358, 5461, 5770, 5791

Molecular Bands:

CH "G band"	4300
CN	3880, 4217, 7699
C ₂ "Swan"	4380, 4738, 5165, 5635, 6122
C ₃	4065
MgH	4780
TiO	4584, 4625, 4670, 4760

Telluric absorption bands:

5860-5990
6270-6370
6850-7400
7570-7700

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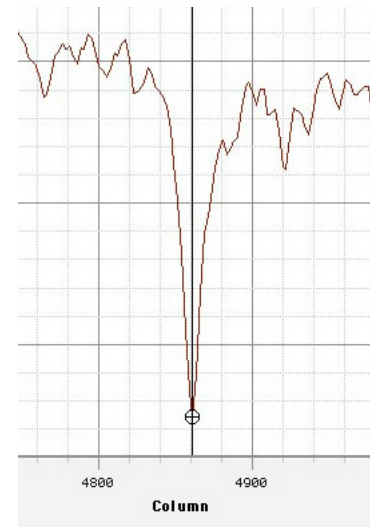
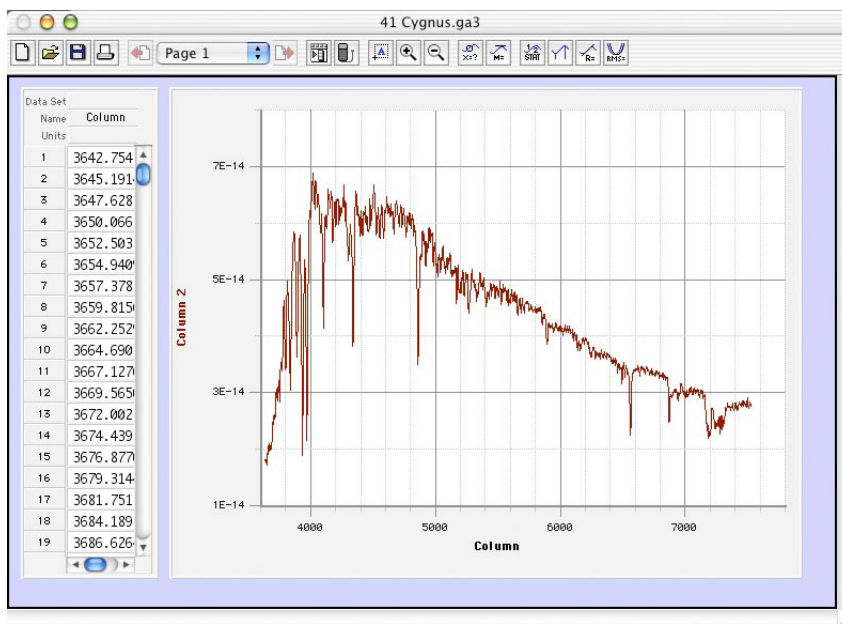


An Example: The Spectrum of 41 Cygnus

Description of the spectrum

“41 Cygnus” is a bright, variable star in the Constellation of Cygnus, the Swan. A spectrum of this star was obtained with the Kitt Peak National Observatory 2.1-meter telescope on July 27th, 2000.

Load the spectrum using the **File/Open...** command. It should look similar to the figure below:

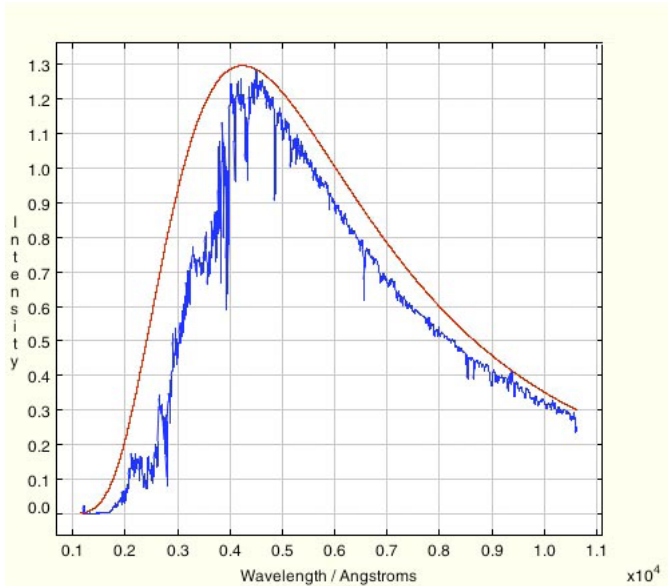


This spectrum measures light from 3600Å to 7500Å (the X-axis). For comparison, the human eye can see from 4900Å to 7000Å. The Y-axis is the flux density per unit of wavelength and is given in units of $\text{ergs/sec/cm}^2/\text{\AA}$. You will notice that the spectrum contains many bumps and wiggles, which correspond to many absorption lines. First we will study the shape of the continuous spectrum and estimate the location of the peak. This is not easy to do because the many absorption lines present have significantly changed the shape of the continuum.

The diagram below shows a plot of what the spectrum might look like without absorption lines. Note that this plot was not generated with Graphical Analysis, or for 41 Cygnus itself, but for a similar star. Also note that the line is always above the data because absorptions remove light from the spectrum. This line is therefore a model of what the continuum looks like without any absorption lines. This plot was generated with a Java applet at:

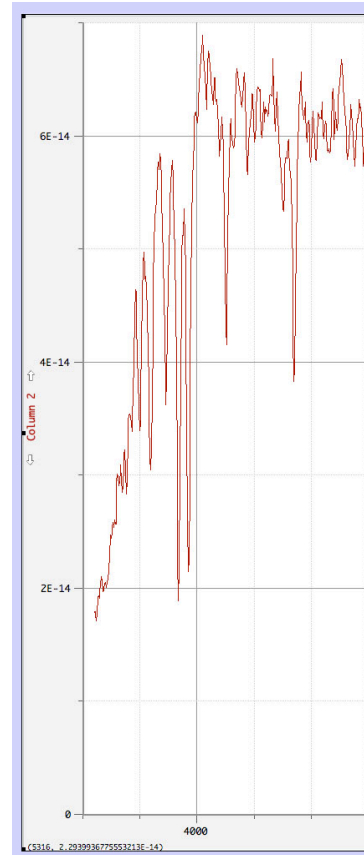
<http://www.jb.man.ac.uk/distance/life/sample/java/spectype/specplot.htm>

Once zoomed in turn on the examine tool and place the cursor at the bottom of the absorption line. The wavelength (X) of this absorption line is 4861Å, which is H β .

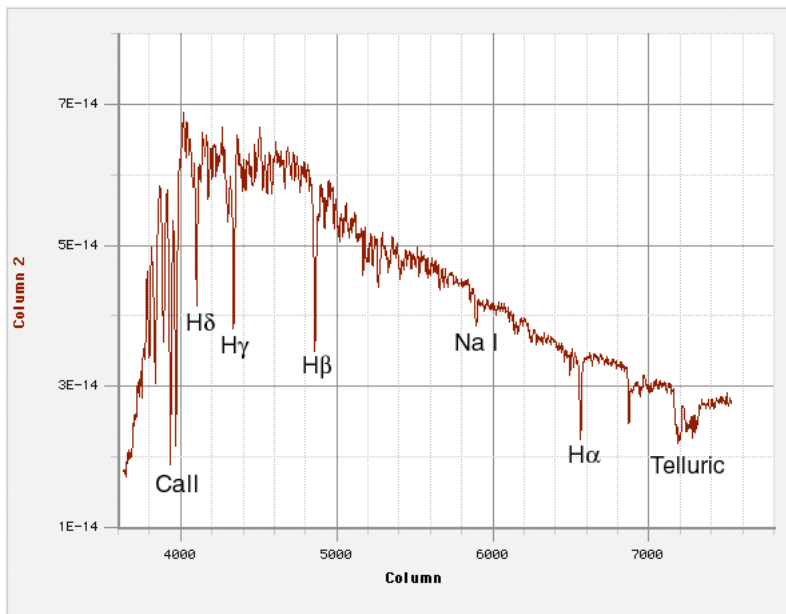


The line is not a precise fit, but we see that the peak of the spectrum occurs around 4200\AA . Using Wien's Law we estimate the temperature of the star to be about 6900 K . Based upon this estimate we tentatively classify it as an *F* class star, although it is hot enough that it might be an *A* class star.

Next we will study the absorption lines. To study the absorption lines more closely you may zoom in on portions of the spectrum and use the examine tool to measure their wavelengths (see right). The Balmer series of Hydrogen lines is strong in this object, as are the $\text{CaII } \lambda\lambda 3933, 3968$ lines (labeled below).



The blue end of the spectrum of the star "41 Cygnus." The absorption lines at 3933\AA and 3968\AA (from CaII) should be considered "very strong." The lines at 4101\AA and 4340\AA (Balmer lines) are "strong." And the line at 4300\AA (G-band) is relatively weak. Lines smaller than this should be considered weak to very weak.



The strength of the $\text{CaII } 3933\text{\AA}$ line is calculated by measuring the flux at the bottom of the absorption line (about $1.9 \times 10^{-14} \text{ erg/s/cm}^2/\text{\AA}$) and a nearby point outside of the line (about $5.8 \times 10^{-14} \text{ erg/s/cm}^2/\text{\AA}$ at 3913\AA). The strength of this line is therefore is about 0.67, or 67%. This qualifies as a very strong line. In comparison, the $\text{NaI } 5896\text{\AA}$ line has a strength of only about 10%, which is relatively weak.

The strong Balmer lines indicate that this must be an *A*, *B* or *F* class star. Metal lines are not very strong in *B* class stars. And in general metal lines are increasingly common in cooler stars. Indeed, many metal lines are present- they account for most of the "bumps and wiggles" in the spectrum. They are too numerous to mention, however G-band $\lambda 4300$ and $\text{FeII } \lambda 4175$ are clearly present. We conclude that this is an *F* class star because it has strong Balmer lines, very strong CaII lines, and several other metal lines (including Na I). This is in agreement with our spectral classification based upon the temperature of the star; and indeed astronomers have classified this star as an *F5*.

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Name(s) _____ Class _____

_____ Date _____

