

Stellar Spectroscopy

The Message of Starlight

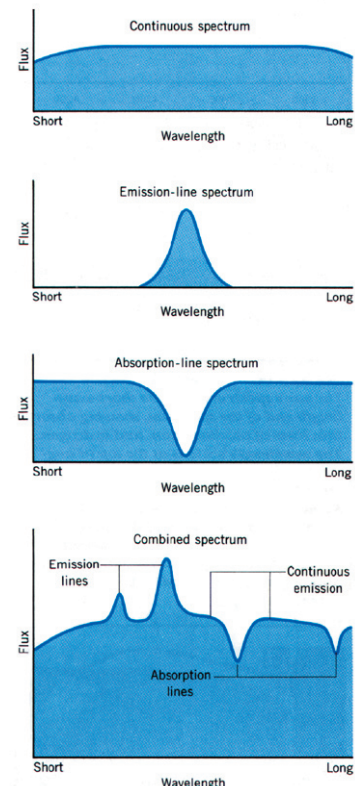


Introduction

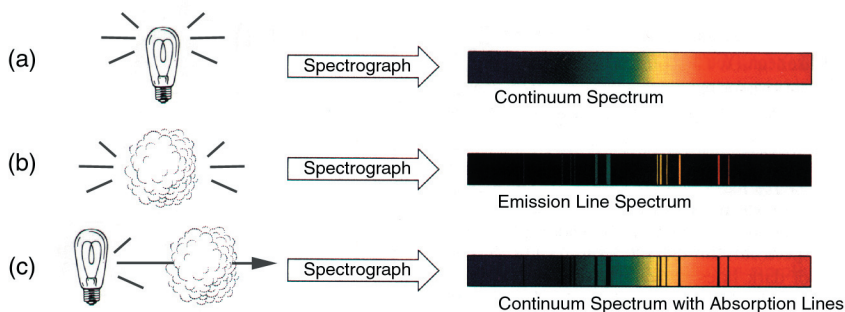
The power of spectroscopy

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.

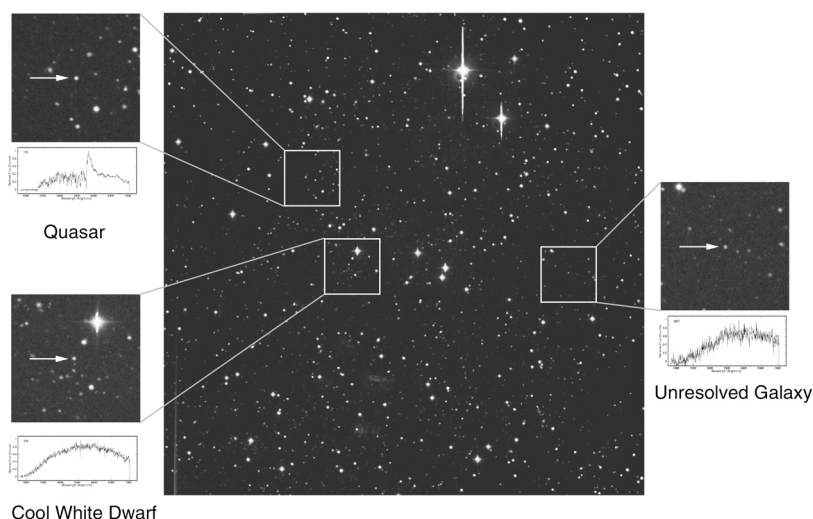


Emission and absorption lines are named after the element responsible for the line (remember that different types of gas produce different lines) and the gas' ionization state. If a gas is heated hot enough its atoms will begin to lose their electrons, either by absorbing photons (particles of light)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

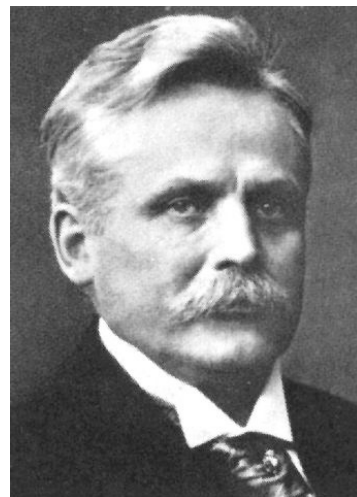
Spectroscopy as an Identification Tool

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.



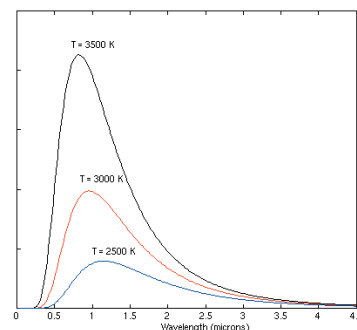
Wilhelm Wien
(1864-1928)

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:

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

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 HeI lines but do not have HeII 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. *A*, *B*

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. $1 \text{ Å} = 10^{-10} \text{ m} = 0.1 \text{ nm}$.



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".

and *F* stars 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:

<u>Class</u>	<u>Spectral Lines</u>
O	Neutral and ionized Helium, weak Hydrogen
B	Neutral Helium, strong Hydrogen
A	No Helium, Strongest Hydrogen, some ionized metals
F	Strong Hydrogen, many ionized metals
G	Weaker Hydrogen, many ionized and neutral metals
K	Weakest Hydrogen, many neutral metals
M	Very weak Hydrogen, strong neutral metals and molecular bands

Because there is a continuum 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. Note that an *A9* star is more like an *F0* star than an *A0* even though an *A9* and *F0* are technically different classes. The Sun, with a surface temperature of 5800 K, is a class *G2* star.

Spectral Class Characteristics:

<u>Class</u>	<u>Color</u>	<u>Temperature (K)</u>
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:

<u>Class</u>	<u>Examples</u>
O	Naos
B	Alnilam
A	Sirius, Vega
F	Canopus, Polaris
G	The Sun, Capella
K	Arcturus, Aldebaran
M	Betelgeuse