

Laboratory 7 - Hertzsprung-Russell Diagram

Materials Used: Scaling transparency, photographs of the Trapezium and Pleiades star clusters, Excel spreadsheet.

Objectives: To investigate Hertzsprung-Russell diagrams; to estimate the ages of stars from the HR diagram; to study the evolution of stars and star clusters.

Discussion: Hertzsprung-Russell (HR) diagrams are plots of stars by *luminosity* (intrinsic brightness) versus *spectral class* (color). The same distribution may be achieved by plotting *luminosity* or *absolute magnitude* versus *spectral class* or *color index* or *surface temperature*. HR diagrams are very useful for determining the age of a group of stars.

A HR diagram of most random groups of stars will display three groups: red giant stars, main sequence stars and white dwarf stars. Figure 1 is a depiction of a HR diagram.

The largest group of stars in any HR diagram is the *main sequence*. The main sequence is common to all HR diagrams and is the longest stage of evolution for any active star. A star on the main sequence derives its energy almost entirely from a nuclear reaction involving the conversion of hydrogen to helium via fusion. A star spends most of its active life on the main sequence.

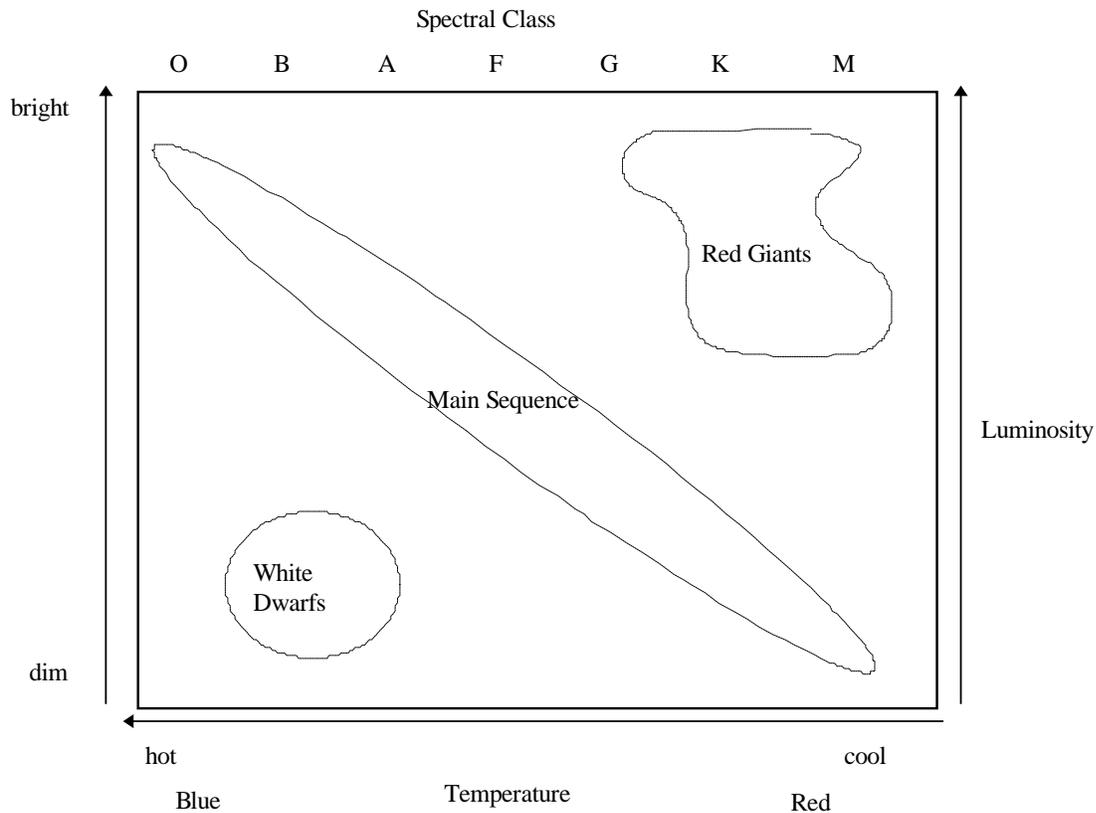


Figure 1. Hertzsprung-Russell diagram.

The HR diagram reveals that bright main sequence stars are also very hot. The hotter main sequence stars are also bluer and more massive. The cooler, dimmer main sequence stars are redder and less massive. Although it is not obvious from the HR diagram itself, the hotter, brighter, more massive and bluer a star is the less time it spends on the main sequence.

It is important to note that *stars do not move up and down the main sequence*. The position of a star on the main sequence is uniquely determined by its mass. When stars leave the main sequence they do so by moving off to the side. High and low mass stars follow very different evolutionary paths upon leaving the main sequence (although both go through a Red Giant phase). Few high mass stars are found on a typical HR diagram anywhere except in the main sequence and red giant regions.

The Red Giant¹ region of the HR diagram is populated by a variety of former main sequence stars. When the hydrogen gas is nearly exhausted in the core of a main sequence star the core begins to cool. As the core cools it exerts less pressure against the enormous mass of the star surrounding it and begins to contract. This gravitational compression of the core increases pressure - causing it to heat up once again (just like squeezing a balloon cause the air inside to heat up). Heat escaping the core causes the gas in the outer parts of the star to expand and the star to swell to enormous size. The star, as a whole, becomes less dense since all but the small central core is expanding. Even though the core of the star is now even hotter than it was before, the surface of the star expands so that the energy per unit area passing through it diminishes. Less energy per unit area results in surface cooling and a redder appearance.

The reenergized core of the star heats up the hydrogen around it to extremely high temperatures - accelerating hydrogen fusion and the subsequent production (and fusion) of helium. This tremendous energy output from the core, coupled with an expanding surface area, results in increasing luminosity (the energy per unit time radiated by the surface of the star). Red Giant stars are found on the upper right side of the HR diagram (low temperature, high luminosity) and are characterized by very large diameters and relatively low surface temperatures.

The final group of stars in a HR diagram is composed of white dwarfs. White dwarfs are former sun-like stars at the end of their lives. Near the end of a low mass star's life, as its supply of helium diminishes, it begins to shrink. Since sun-like stars do not have enough mass to fuse elements heavier than helium they undergo a complete collapse when their conversion of helium to heavier elements is nearly complete. During this process the star ultimately attains enormous density. White dwarfs are compact objects about the size of Earth but containing the mass of the sun. This is possible because the gases in the interior of these stars are completely *ionized*, i.e., stripped of electrons. Most of the mass of an atom (~99.98%) is concentrated in the nucleus, but most of the volume is occupied by orbiting electrons. In this state it is possible to pack nuclei very close together resulting in a substance of extremely high density. The density of a typical white dwarf star is over a million times that of water. A single tablespoon of white dwarf material would weigh several tons on Earth.

¹ The Red Giant group is actually composed of two subgroups: Red Giants and Red supergiants.

Although white dwarf stars are extremely hot they are not very luminous because of their compact size. This feature makes white dwarfs difficult to observe through optical telescopes (Sirius B is one of the few white dwarfs visible through all but the most powerful optical telescopes). Fortunately white dwarfs are powerful x-ray sources and easily detected with x-ray telescopes.

There are two other possible end states of stellar evolution: neutron stars and black holes. These are remnants of high mass stars, neither of which is luminous enough to appear in the HR diagram.

In summary:

- There are three main groups of stars on the HR diagram: main sequence, red giant and white dwarf.
- A star begins its evolution on the HR diagram at a point on the main sequence determined by its mass.
- Sun like stars evolve into a red giant stage and end their active lives as white dwarfs.

Constructing a HR Diagram

In this exercise you will produce two HR diagrams: one of the Pleiades Cluster (located in the Taurus constellation) and one of the Trapezium Cluster (located in Orion). To produce your HR diagrams you will need to determine the *absolute magnitude* and *color index* of a sample of stars in each cluster. By assuming that all of the stars in the cluster are at about the same distance from us (a reasonable assumption), the photographic magnitude of each star may be used as a measure of the absolute magnitude, i.e., the size of a star in the photograph may be related to its intrinsic brightness; the bigger the star in the photograph, the greater its brightness. If the same cluster is photographed with two films of different color sensitivity one may find the color index (temperature) by comparing the sizes of the images. All that is needed to produce a HR diagram are two black and white photographs of each star cluster. These have been provided for you.

Once you have produced your HR diagrams you can estimate the age of the clusters by noting how many of the stars have left the main sequence and become red giants (you will not be able to see any white dwarfs in the photographs). The absence of any stars on the upper left of the main sequence, for example, and the presence of a large number of red giants indicates a highly evolved, older cluster. The lack of stars outside of the main sequence indicates a young cluster.

The Pleiades Cluster

Two different positive prints (black sky, white stars) of the Pleiades Cluster have been provided. One print is from a photographic negative made without a filter and the other from a photograph negative made with an amber filter. The unfiltered photograph has slightly larger star images. Please do not mark these prints.

Pick stars that you are sure are members of the Pleiades cluster (stars close to the center of the print). Be sure to eliminate any stars that appear single on one print but can be resolved as

two stars on the other. Obtain a measurement of the size of each star you choose from both photographs with the scale on the transparency that has been supplied to you. This scale is graduated so that the largest measurement is one centimeter.

Subtracting the measurement for photographic magnitude (unfiltered) from the measurement for filtered magnitude yields the color index of the star: $Color\ Index = M_f - M_p$.

	A	B	C	D	E	F	G
1	Pleiades Data			Trapezium Data			
2	Photographic Magnitude	Filtered Magnitude	Color Index		Blue Magnitude	Red Magnitude	Color Index
3			0				0
4			0				0
5			0				0
6			0				0
7			0				0
8			0				0
9			0				0
10			0				0
11			0				0
12			0				0
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Figure 2. HR.xls

A spreadsheet, HR.xls (Figure 2), has been prepared to assist you. Enter your measurements in the columns labeled **Photographic Magnitude** and **Filtered Magnitude** in the **Pleiades Data** section of the spreadsheet. The spreadsheet will compute the color index. Collect data on ten to twelve stars. The spreadsheet will construct a plot of both Photographic Magnitude vs. Color Index and a Hertzsprung-Russell diagram based your data. You may access these plots by clicking the appropriate tabs at the bottom of the screen. Be sure to print copies for your binder.

The Trapezium Cluster

The photographs of this cluster (from the Palomar Sky Survey) are negative prints - white sky, black stars. The plate numbers are in the upper left hand corner of each print. The plates provided are E1477 and O1477. The E plate is red sensitive and the O plate is blue sensitive.

The Trapezium cluster appears around the gas cloud on the right of each print. You should choose for measurement foreground stars around this cloud and proceed as before. In these photographs the Trapezium cluster appears to be more spread out than did the Pleiades Cluster in the photographs you previously examined. But since the scale of the photographs is different this comparison is invalid. The Trapezium cluster is actually much smaller than the Pleiades cluster.

Enter your data in the Trapezium section of the HR spreadsheet in the columns: blue magnitude, red magnitude. Collect measurements on ten to twelve stars. This time the color index is the difference between the red and blue magnitudes: **Color Index** = $M_r - M_b$. The spreadsheet will compute the Color Index of each star and produce plots of Blue Magnitude vs. Color Index and a HR diagram of the cluster.

Analysis

Estimate the age of the Pleiades and Trapezium clusters from your HR diagrams. Both are open clusters. What generalizations can you make about the age of open clusters?

The Pleiades cluster (M45) appears relatively young since its HR diagram is composed almost entirely of main sequence stars. The Pleiades cluster is, in fact, composed almost entirely of young, spectral class B stars that are very luminous. The Pleiades are relatively close (about 440 LY) and young (about 100 million years old).

The Trapezium cluster (in M42) is composed almost entirely of spectral class B and O stars and is even younger than the Pleiades cluster at a mere 1 million years. The Trapezium is located some 1600 LY distant.

Open clusters are relatively young clusters of stars. Open clusters are associated with star-forming regions of our galaxy (many near the spiral arms). Open clusters tend to lose stars over time, which means that there are no extremely old open clusters.

Exercises

1. What determines the position of a star on the Main Sequence?

2. What type of nuclear reaction powers all stars?

3. According to your HR diagrams, open clusters are composed primarily of what type of stars?

4. What type of star is located on the lower left of a HR diagram?

5. What does the term "active life" of a star mean?

6. Where are the hottest stars on a HR diagram? The brightest?

7. Where will our own sun end up on the HR diagram?

8. Why is it reasonable to assume that all of the stars in the clusters in both photographs are about equally far away?

9. Why don't white dwarf stars appear in any photographs in this exercise?