THE HR DIAGRAM

THE MOST FAMOUS DIAGRAM in ASTRONOMY

Mike Luciuk

1.INTRODUCTION

Late in the nineteenth century, astronomers had tools that revealed a great deal about stars. By that time, advances in telescope design and photographic emulsions were becoming mature. They were able to take spectral images of stars which revealed their composition and they could determine the distances of the closer stars through their angular displacements (parallax) as the Earth orbited the Sun. The Stefan-Boltzmann luminosity law and Wien's peak wavelength displacement law were well known in the scientific community by century's end. Astronomers began to classify stars based on spectral differences, and although these classes were known, their significance was not. Remember, knowledge about the existence of other galaxies, the Hubble redshift, quantum mechanics, and the fusion process generating stellar energy came in the third and fourth decades of the twentieth century.

In 1911, the Danish astronomer Ejnar Hertzsprung (1873-1967) plotted a color-magnitude diagram, discovering the distinction between main sequence and giant stars while studying the Hyades cluster. Colors were determined by the ratio of brightness from two filters, and apparent magnitudes were normalized to absolute magnitudes. Two years later, the American astronomer Henry Norris Russell (1877-1957), using similar techniques, was able independently to distinguish between giant and main sequence stars. Stellar color and spectral class are related to temperature. Therefore, current versions of the Hertzsprung- Russell (HR) diagram utilize one or more of the three in the x-axis versus luminosity in the y-axis.

2. HR DIAGRAM BASICS

Figure 1 illustrates the general layout of an HR diagram. Here, the x-axis is in Kelvin, but sometimes stellar color or spectral class is used. The y-axis is in units of the Sun's luminosity, but absolute magnitude is employed very often. Absolute magnitude is the apparent magnitude of a star that's 10 parsecs (~31.6 ly) distant. Note that temperatures decrease to the right. Stars in the left are hotter; those at the top are more luminous.
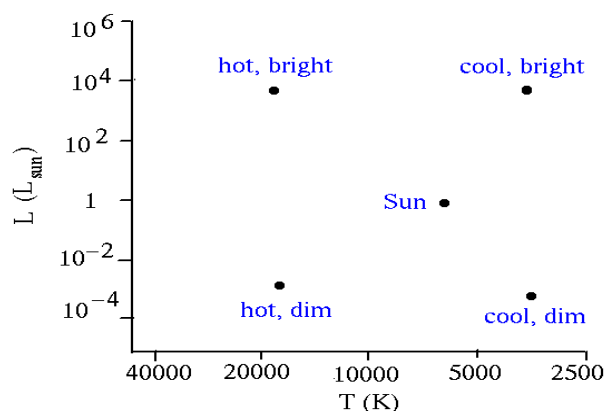

Figure 1. Basic HR Diagram Layout

It's important to understand how stellar colors are determined. Since the spectrum of stars depends on temperature, astronomers have devised a method of determining their temperature via filters. Figure 2 illustrates the wavelength response of standard U (ultraviolet), B (blue) and V (visual) filters. Magnitude measures through such filters are used to create a color index (CI) for a star. An example is the B-V color index, from which temperature can be derived. The Sun's magnitude via the B filter = 2.77 and its
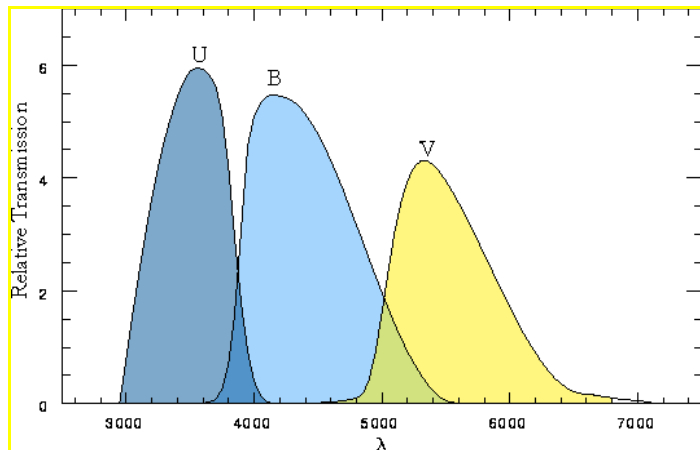
Figure 2. UBV Bandpass, Angstroms
http://web.njit.edu/~gary/321/Lecture2.html

magnitude via the V filter = 2.14, so its B-V index is 2.77-2.14 = 0.63. The color index is positive for stars redder than a white star like Vega (A0 V stars on the HD diagram) and negative for stars bluer than a white star like Rigel.

Spectral classes in HR diagrams are described in Table 1. The table, developed in 1901, lists seven classes: O, B, A, F, G, K, M in order of decreasing temperature. In 1999, two more classes were added to the classical Harvard sequence for cool red and infrared stars, **L** (~2000 K) and **T** (~1000 K), respectively. Each class is divided into ten parts, 0-9, also in order of decreasing temperatures. For example, the Sun is in the G2 spectral class.

The Harvard Spectral Sequence			
Spectral Class	Distinguishing Characteristics	Temperature (K)	Example
O	Ionized He and metals; weak H	28,000 - 60,000	zeta Orionis
B	Neutral He, ionized metals, stronger H	10,000 - 28,000	Rigel, Spica
A	Balmer H dominant, singly-ionized metals	7500 - 10,000	Sirius, Deneb
F	H weaker, neutral and singly-ionized metals	6000 - 7500	Procyon, Canopus
G	Singly ionized Ca, H weaker, neutral metals	5000 - 6000	Sun, Capella
K	Neutral metals, molecular bands begin to appear	3500 - 5000	Aldebaran, Arcturus
M	Ti oxide molecular lines; neutral metals	< 3500	Antares, Betelgeuse

Table 1. The Harvard Spectral Sequence
http://csep10.phys.utk.edu/astr162/lect/hr/hr.html

3. HR DIAGRAM DETAIL

Figure 3 illustrates the full scale of an HR diagram. The x-axis at the top utilizes both spectral class and temperature while at the bottom, the x-axis uses the B-V color index. The y-axis on the left uses luminosity in solar units while absolute magnitudes are at right.

This is a plot of 22,000 stars from the Hipparcos Catalogue together with 1,000 low-luminosity stars (red and white dwarfs) from the Gliese Catalogue of Nearby Stars. The ordinary hydrogen-burning dwarf stars like the Sun are found in a band running from top-left to bottom-right called the Main Sequence. Giant stars form their own clump on the upper-right side of the diagram. Above them lie the much rarer bright giants and supergiants. At the lower-left is the band of white dwarfs - these are the dead cores of old stars which have no internal energy source and, over billions of years, they slowly cool down towards the bottom-right of the diagram. (http://www.atlasoftheuniverse.com/hr.html)
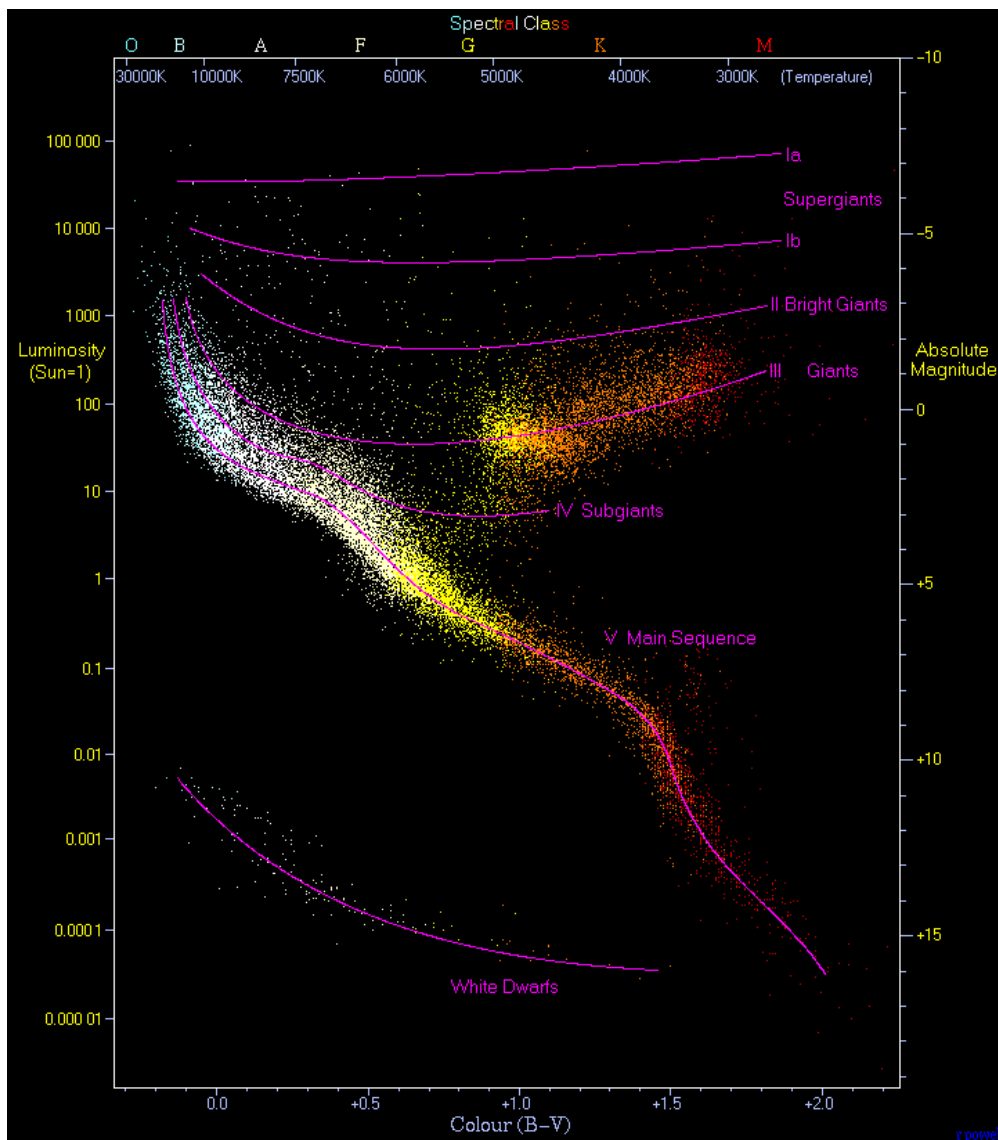.

Figure 3. The HR Diagram
http://www.atlasoftheuniverse.com/hr.html

The HR diagram in figure 3 shows the positions of five luminosity classes of stars as follows (http://www.atlasoftheuniverse.com/hr.html):

I Supergiants

Stars that are very massive and very luminous near the end of their lives. They are subclassified as Ia or Ib, with Ia representing the brightest of these stars. These stars are very rare - one in a million stars is a supergiant. The nearest supergiant star is Canopus (F0Ib) 310 light years away. Some other examples are Betelgeuse (M2Ib), Antares (M1Ib) and Rigel (B8Ia).

II Bright Giants

Stars which have a luminosity between the giant and supergiant stars. Some examples are Sargas (F1II) and Alphard (K3II).

III Normal Giants

These are mainly low-mass stars at the end of their lives that have swelled to become a giant star. This category also includes some high mass stars evolving on their way to supergiant status. Some examples are Arcturus (K2III), Hadar (B1III) and Aldebaran (K5III).

IV Subgiants

Stars which have begun evolving to giant or supergiant status. Some examples are Alnair (B7IV) and Muphrid (G0IV).

V Dwarfs (Main Sequence and White Dwarfs)

All normal hydrogen-burning stars. Stars spend most of their lives in this category before evolving up the scale. Class O and B stars in this category are actually very bright and luminous and are generally brighter than most Giant stars. Some examples are the Sun (G2V), Sirius (A1V), and Vega (A0V).

The conventional way to denote stars is to specify their spectral class followed by their luminosity class Roman numerals as seen in the preceding examples.

Figure 4 illustrates the range of stellar sizes in an HR diagram. Note the *Radius = R_0* line through the Sun. All stars on that line have the same size as the Sun. The slope of the line occurs because luminosity varies as T^4. The parallel lines, spaced 100 solar luminosity units (five magnitudes) apart are due to factors of ten differences in star radii. Stars on the main sequence (dwarfs) range in size from about 0.0005 to 12 times the radius of the Sun while supergiant stars can be ~3,000x the Sun's size. Note that while Rigel and Betelgeuse have about the same luminosity, Rigel is about 3x hotter while Betelgeuse is about 9x larger.
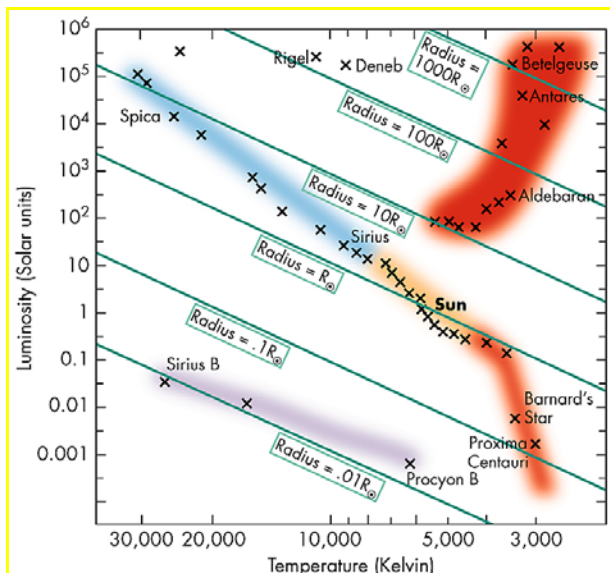

Figure 4. Star Sizes
http://www.physics.isu.edu/~hackmart/spectral_class.pdf

Figure 5 plots solar mass ratios of main sequence stars versus their solar luminosity ratios. The only direct way to measure stellar mass is through binary stars via Newton's form of Kepler's third law. The Sun is the circle near the center of the graph. An approximate relationship is that luminosity is roughly proportional to the 3.5th power of mass:

$$L \propto M^{3.5}$$

So a star with a mass twice the Sun's would have a luminosity ~11.3x greater than the Sun. For half the Sun's mass the luminosity would be ~0.09x the Sun.
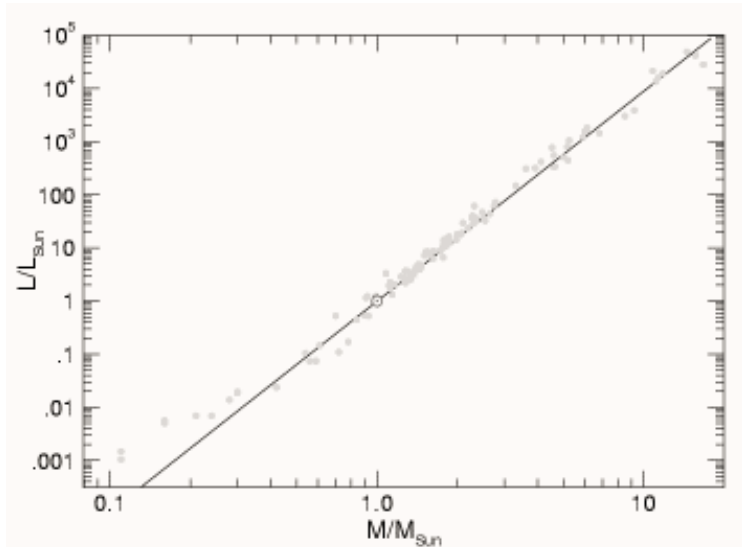
Figure 5. Main Sequence Mass-Luminosity
http://www.astronomy.ohio-state.edu/
~pogge/Ast162/Unit2/structure.html

Because massive stars consume their fuel more rapidly than less massive stars, their lifetimes are correspondingly much shorter:

$$T_{LIFE} \propto M^{-2.5}$$

So a star twice as massive as the Sun has a lifetime ~0.18x the Sun's 10 billion years. For a star 50% the Sun's mass, the lifetime would be ~5.6x the Sun's. The most massive main sequence O stars have lifetimes much less than 100 million years. The lifetimes for stars on the main sequence are now well known.

4. STELLAR EVOLUTION

PRE-MAIN SEQUENCE
Figure 6 illustrates the movements over time of protostars prior to entering the main sequence and starting the hydrogen fusion process. The point of entry to the main sequence is called the "zero age main sequence" or ZAMS. These Hayashi tracks are shown for protostars of various masses, which determine where in the main sequence a protostar enters. The track for stars of the Sun's mass are detailed as follows:
(http://outreach.atnf.csiro.au/education/senior/ astrophysics/ stellarevolution_formation.html)

1. Initial collapse of a cloud causes it to heat up and become a protostar. Although cool, it is very large (perhaps 20× the diameter of the Sun) thus its surface area is so great that its overall luminosity is very high, maybe 100× its main sequence luminosity.

2. As it radiates away energy, gravitational collapse pulls the protostar inwards rapidly. Its temperature rises but this is offset by the decrease in size so that overall luminosity decreases significantly as shown by the vertical drop on the H-R diagram.

3. Once the core temperature reaches 10 million K, coulombic repulsion between the now ion-ized hydrogen atoms (protons) is overcome, and nuclear fusion commences. Hydrogen fuses to form helium nuclei, releasing en-ergy in the process. Initially, the increased outward radiation pres-sure is still insufficient to halt gravitational collapse, but it does slow it down. The star's surface temperature increases signifi-cantly, compensating for the drop in size so that its luminosity in-creases slightly. The star's track moves up slightly and to the left on the H-R diagram over 10 mil-lion years.

4. As the rate of core fusion in-creases due to higher core tem-perature, the outward gas and ra-diation pressures eventually match the inward gravitational force. The star attains a state of hydrostatic equilibrium and settles down onto the main sequence. This stage may take a few tens of millions of years.
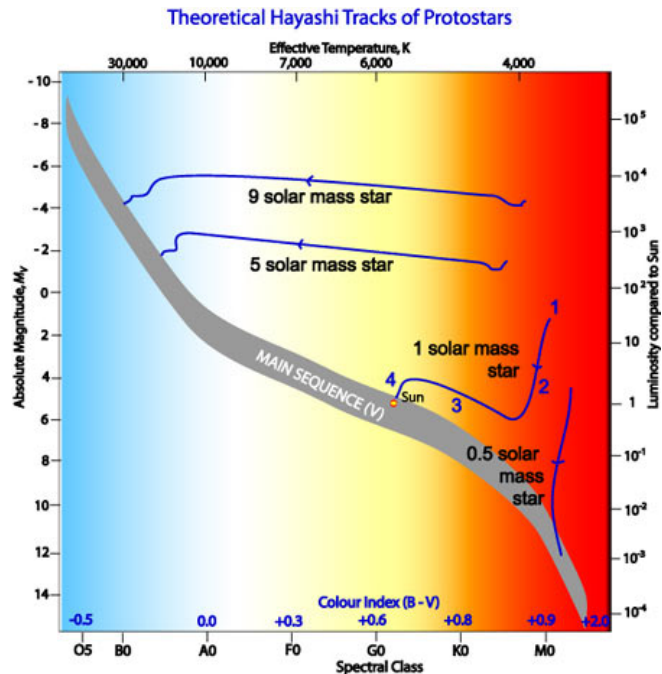

Figure 6. Protostars Entering The Main Sequence
http://outreach.atnf.csiro.au/education/senior/
astrophysics/stellarevolution_formation.html

POST-MAIN SEQUENCE

Mass is again the key to stars' tracks when they deplete their hydrogen and leave the main sequence as illustrated in Figure 7. Their surface temperatures drop as their size increases, and they become red giants for the next stage of their evolution. The most massive stars reach the supergiant stage while even smaller stars like the Sun become giants for a time. The largest stars ultimately become black holes while medium stars become neutron stars. Solar mass stars expand to sizes exceeding an astronomical unit before becoming white dwarfs and ending in the dim reaches of the HR diagram.
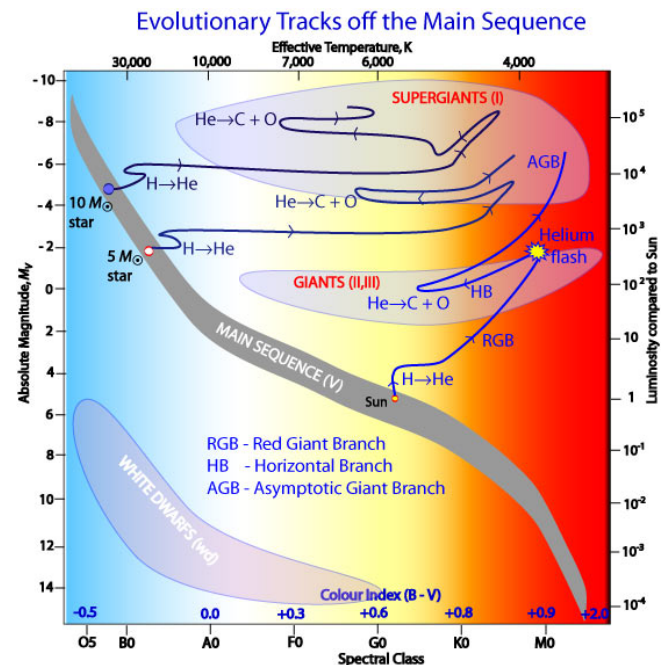

Figure 7. Stars Leaving the Main Sequence
http://outreach.atnf.csiro.au/education/senior/
astrophysics/stellarevolution_postmain.html

EVOLUTION of STAR CLUSTERS

Star clusters are formed from giant molecular clouds and dust. As a result, the stars in a cluster are the same age and about the same distance from Earth, but they develop in a range of masses. Four different open star clusters are plotted in the figure 8 HR diagram. We can assess the age of each cluster by its turnoff point, the place where its stars begin to leave the main sequence. The higher (more luminous) the turnoff point on the main sequence, the younger the cluster. This is because more luminous stars on the main sequence, being more massive, have shorter lifetimes. For example, The Perseid h + chi double cluster's main sequence turnoff occurs at about

Figure 8. Multi-Cluster HR Diagram
http://web.njit.edu/~gary/202/Lecture17.html

spectral class O9 indicating an age of ~14 million years. The Pleiades cluster's turnoff point is at about B6, for a cluster age of ~100 million years. The turnoff for the Hyades cluster occurs at about A3 with an age of ~650 million years. Finally, NGC 188's turnoff at about F5 indicates a ~7 billion year old cluster.
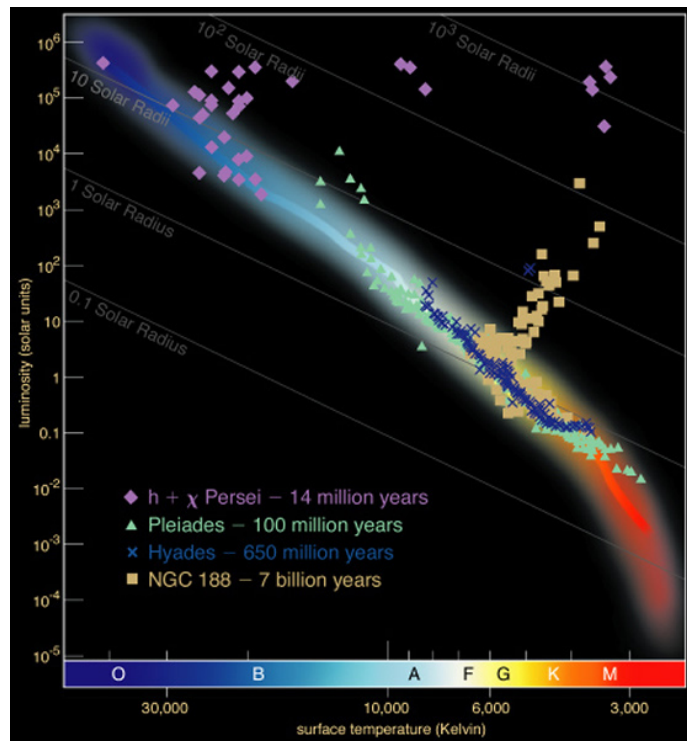
Globular clusters are much older than open clusters. When plotted on an HR diagram, they typically have no remaining O, B, A, F class main sequence stars, and their turnoff occurs in the G class. This implies that ages of some globular clusters are close to that of the universe.

5. SUMMARY

In the century since the bases of HR diagrams were first developed, they have become invaluable in the study of stars. For astronomers, a star's location in an HR diagram provides the same depth of insight as for chemists examining an element in the periodic table. It relates hydrogen fusing stars' temperatures, colors and spectral classes with their luminosities, thereby providing insights into their evolution. A star's position in the diagram can indicate its composition, surface temperature, intrinsic brightness, size, mass, lifetime, and evolutionary status. That's a lot of information from a diagram. It's been invaluable in determining the age of various star clusters. Apparent magnitudes can be used if absolute magnitudes are not available, since all stars in a cluster are roughly equally distant.

6. REFERENCES

http://asterism.org/, Tutorials & More, *Astronomical Magnitudes*
http://csep10.phys.utk.edu/astr162/lect/hr/hr.html
http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_postmain.html
http://outreach.atnf.csiro.au/education/senior/%20astrophysics/stellarevolution_formation.html
http://stars.astro.illinois.edu/sow/hrd.html
http://web.njit.edu/~gary/202/Lecture17.html
http://web.njit.edu/~gary/321/Lecture2.html
http://www.astronomy.ohio-state.edu/
http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit2/structure.html
http://www.atlasoftheuniverse.com/hr.html
http://www.physics.isu.edu/~hackmart/spectral_class.pdf
http://zebu.uoregon.edu/~soper/Stars/hrdiagram.html