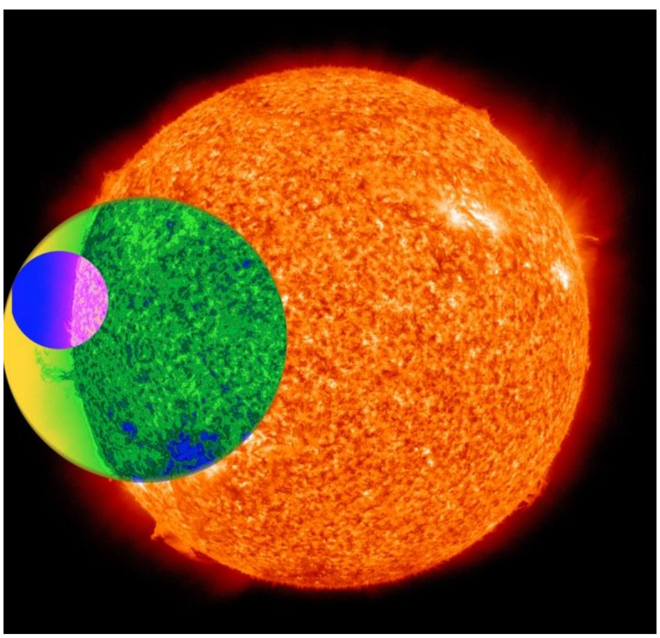
Observing Stellar Evolution



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Introduction

Everything that you see in the night sky is visible to you because of light from a star. The stars themselves, nebulae, planets, moons, are visible because of starlight. Even dark nebulae are visible because they block the illumination of stars or other objects lit up by stars. We exist because early generations of stars generated the elements that make up our planet and the chemical elements required for life. It is not an understatement to say that we exist because stars exist.

The Observing Stellar Evolution Observing Program will be of interest to beginning observers as well as more experienced observers. This program requires that you observe all the objects, even those you have already observed. The purpose of this program is to develop in the observer an appreciation for the most common objects that they see in the night sky – stars. Stars, like us, are born, live their lives and end their lives. Understanding this 'stellar evolution' is important to understanding how the universe works.

Some of the objects in this observing list are on other Astronomical League observing lists, so you may have already observed some of the objects. In addition to performing the observations, you will have enough information to put each object into the context of stellar evolution. In the end, observing is something you do in your mind. It's not about simply seeing the object, it's about understanding what the object is, why it is important, why it is interesting and how it fits into the story. Once you do, you'll be able to say 'oh, WOW' for objects that you may have overlooked or may have underappreciated so far.

Many of the objects in this list are easy naked eye objects, but some will require a small telescope and some patience to find. Not all stars are bright, and end-of-life stars can be particularly dim. The bright objects will generally be visible from a home in the city or in the suburbs, the dimmer objects will require reasonably dark, but not pristine, skies. A few of the objects will be better seen under clear dark skies with a large telescope.

Rules and Regulations

All members of the Astronomical League can receive a certificate and a pin for the completion of this program. You can be a member of the A.L. because you are a member of an affiliated club, or you can be a member of the A.L. 'at-large'. The observing list for this program is divided into several sections each illustrating a separate phase of stellar evolution. To meet the objective of this program it will be necessary for you to observe the objects in each of the categories. The observations must be made in the context of completing this program; **objects that you have already observed must be observed again to complete this program.** You will be observing the objects with a new understanding of the place of the object in the story of the universe, with 'new eyes' you may say.

A total of 100 objects must be observed to complete this program. A log sheet that meets the requirements of this program is at the back of this manual.

Your observing log sheet must include this information for each of the objects:

- Object name
- Date & Time (local or Universal Time)
- Observing Site – City, Town, State, Country or Latitude and Longitude
- Telescope used to make the observation – generic description is ok (Examples: 8" SCT, 4" refractor, 15" Reflector, etc.)
- Magnification used
- Object description

As part of this manual we'll be looking at, and understanding the HR diagram. This diagram was developed independently by Ejnar Hertzsprung and Henry Norris Russell in about 1910. If there is a lot to be gained from the study of the HR diagram, its concept is easy. The X (horizontal) axis of the chart is temperature of the star (color and temperature are the same thing) and the Y (vertical) axis of the chart is the luminosity of the star. The luminosity is the intrinsic brightness of the star. A star's magnitude is the brightness of a star as seen from earth, so a high luminosity star that's very far away may look dim to us and a lower luminosity star that is nearby may appear brighter to us.

Of course, I hope that you will enjoy learning about stellar evolution and observing the objects in this program as much as I have enjoyed developing the program.

Some terms you need to know

- **Stellar evolution** – refers to the stages in the lifetime of one star. When biologists talk about evolution they mean intergenerational evolution. While stars change from one generation to the next, the focus of this program is stellar lifetimes.
- **Burning** – The materials that comprise stars do not 'burn' in any ordinary sense of the word. What's really going on is nuclear fusion. Hydrogen becomes helium which becomes carbon and oxygen, and so on. So, when astronomers talk about hydrogen 'burning' they really mean that hydrogen is being fused to helium (nuclear fusion) and converting lost mass to energy. This is how main sequence stars work. More on this later.
- **Ash** – the product of 'burning'. Helium is considered the 'ash' of hydrogen burning.
- **Luminosity** -- is a measure of the power of the star. You can think of the luminosity as the intrinsic brightness of the star. If all stars were the same distance from us, the only thing that would affect their apparent brightness (the brightness we see) would be the luminosity of the star. Luminosity is usually measured in comparison to solar (the Sun) luminosity.
- **Main sequence** – Stars on the 'main sequence' are mid-life stars. About 90% of the lifetime of a star is spent on the main sequence. More on this when we review the HR diagram.
- **Planetary nebulae** – have no relation to planets. These are the near-final life stages of low mass stars.
- **Solar masses** – Stars are talked about in terms of their equivalent solar (our Sun) mass. It's a colloquial way to talk about stars, but that is the way it's done.

- **Metals** – This is an odd term, but astronomers talk about the chemical elements that comprise a star. Any element heavier (in the atomic sense) than helium is called a 'metal', even though this does not match our day-to-day use of the word.
- **Kelvin (temperature)** – This temperature scale is based on an absolute zero temperature – the temperature at which all molecular activity stops. Kelvin temperature is equal to Celsius temperature + 273.15 degrees (0 degrees C = 273.15 K). When we talk about stars, we talk about temperatures in the thousands of degrees Kelvin, so for practical purposes when considering the temperature of stars, Kelvin and Celsius are close enough to be the same. Astronomers use Kelvin temperatures and those will be used in this manual.
- **Scientific notation** – Because large numbers are hard to write – too many digits – and hard to read, scientists and engineers use what is called 'scientific notation' to write very large and very small numbers. Here is how it works. You see a number, say 2.5 then a 10 with an exponent, like this 10^8, so the entire number would be 2.5×10^8. The 10^8 number means 8 zeroes, 100,000,000, or 100 million. So 2.5×10^8 is equal to 250,000,000. For very small numbers, scientists use a negative exponent. For example 5×10^{-3} means that you have to move the decimal point 3 places to the left to get the decimal equivalent, and the answer is 0.005.

Stellar Catalogs

Many stars have multiple names and appear in multiple catalogs. It is confusing. Software that maps the sky can use one or more of the designations to identify a star, but not all. Astronomy is an old science and over time many names and catalogs have been developed. Those of us who are amateur astronomers will simply have to learn to live with this system.

To help you along the way, here are some of the more common catalogs.

Proper names – such as Betelgeuse, Aldebaran, and Altair. These names are often Arabic in origin, sometimes they're Greek or Latin. There is no scheme to these names.

Bayer designation – created by Johann Bayer in the early 1600's. The designation is a Greek letter (Alpha, Beta, Gamma, etc.) followed by the possessive case of the constellation's name. Alpha Orinis is the star Betelgeuse. Usually, but not always, in the order of brightness within a constellation.

Flamsteed designation – created by John Flamsteed in the early 1700's. Similar to the Bayer designation except numbers are used in place of Greek letters, and stars are designated in increasing Right Ascension (RA) order. Examples: 31 Ori, 42 UMa.

SAO – Smithsonian Astrophysical Observatory – This catalog was published in 1966. The catalog is organized by Declination (Dec) and RA and stellar names are simply the letters SAO followed by numbers. Examples: Rigel is SAO 131907, and Altair is SAO 125122.

HIP – Hipparcos Catalog – the result of a European Space Agency's mission to measure star positions. This high precision catalog is from the mid 1990's. Examples: HIP 14576 is Algol, and HIP 24608 is Capella.

Gliese – A catalog of 'nearby' stars, out to about 75 ly. Created by Wilhelm Gleise in the mid 1950's in order of RA. Example: Gl 33 is HD 4628

Draper Catalog – Created by Henry Draper in the early 1900's. It contained spectroscopic data for the stars in the catalog. It is ordered by RA. Examples: HD 39801 is Betelgeuse, and HD 172167 is Vega.

Variable stars – first one in a constellation is called R. Example: R Crb (the first variable in Corona Borealis), then S, T, U, V, W, X, Y, Z. After that the naming starts over with RR. Example: RR Lyr. Then RS, RT… etc. is used. When all letter combinations are used the next star is labeled V335.

Ross Catalog – high proper motion stars. Catalog was created c. 1940. Example: Ross 248 is HH And (variable).

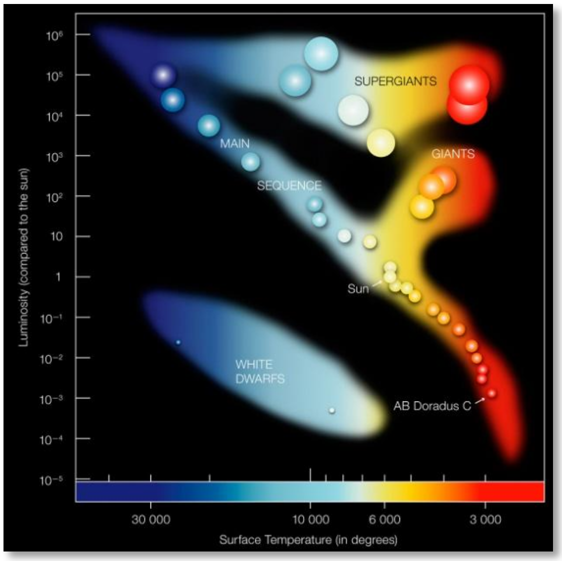
Lalande Catalog - Example: Lalande 21185 is SAO 62377.

The HR Diagram

In the early 1900's there was quite a bit of data about stars. We had spectroscopic data for stars and we had distances to some relatively nearby stars (developed by observing the parallax of the stars). The challenge was to organize this data in a way that helped us understand stars.

In about 1900 Ejnar Hertzsprung and Henry Norris Russell decided independently that plotting the intrinsic brightness of stars (the luminosity) on the Y axis and the temperature of the stars on the X axis might provide some interesting insight into how stars are categorized and how they work. When they did this, they found that most stars fell along a line that went from blue and hot (at the upper left) to red and cool (at the lower right). This line is called the 'main sequence'. The 'main sequence' is where a star stays for 90% or so of its lifetime. As a star ages, its location in the diagram changes. This is a function of its characteristics (color and temperature); this does not represent a change in the star's position in space.

It's not clear why the chart was created with higher temperature stars at the left and lower temperature stars at the right.



Credit European Southern Observatory

From Wikimedia Commons

The H-R diagram also accommodates stars that are not on the main sequence. These may be late-in-life stars or they may be new stars, ones that are just shy of joining the main sequence.

In some work performed in the late 1800's and early 1900's at Harvard University, Williamina Fleming arranged stars based on the hydrogen content of the star. They were identified with the letters of the alphabet, with 'A' stars having the most hydrogen and those with later letters in the alphabet having progressively less hydrogen. Following this work, Annie Jump Cannon, also at Harvard, rearranged the list by the temperature of the star. It turned out that the hydrogen content is higher in mid-temperature stars than in very hot or very cool stars. So, early letters in the alphabet represent mid-temperature stars. When stars were re-ordered by temperature the original designations were retained but the letters became scrambled.

Today, we continue to use this scheme for the temperature / color of stars that uses the letters in this order – OBAFGKM – from bluest and hottest to reddest and coolest. The standard pneumonic for remembering this sequence is 'Oh Be A Fine Girl/Guy, Kiss Me'.

There will be more information on this diagram in the section on main sequence stars, and the HR diagram will be used throughout this manual to illustrate the various stages in the lifetime of a star.

Stellar Evolution in a Nutshell

All stars are formed from cosmic gas, mostly hydrogen and some helium.

Low mass stars (up to 8 solar masses)…

Are on the main sequence for billions to trillions years (Sun for 10 b years).
At the end of their life they become a red giant star.
Then they leave the Red Giant phase via the Horizontal Branch.
They become Carbon Stars and blow off their outer atmosphere.
In this stage they are Planetary Nebulae.
They run out of fuel and become a white dwarf.

When they run out of heat and they become a black dwarf.

High mass stars (more than 8 solar masses)…

Live fast die young. They may remain on main sequence only a few million years.
They go through many phases of evolution quickly, creating heaver elements as they go.
When the core becomes iron, they explode as a supernova.
They end life as a neutron star or a black hole.

Stellar Birth

To say that stars are born, live out their lives, and die should not come as a surprise. How this happens, as we shall see, depends on the mass of the star. There are some common ideas associated with stellar birth that are independent of the ultimate size of the star.

The universe consists mainly of two elements, hydrogen and helium. About 74% of the universe is hydrogen, and 24% of the universe is helium by mass. What is the remaining 2%? The answer is that remaining 2% is everything else – including oxygen, carbon, and all the heavier elements. With the universe in great supply of hydrogen and helium it is easy to imagine that stars are formed out of this material.

The universe is lumpy, and this is important. There is not a uniform distribution of the hydrogen and helium in the universe. If you get a big enough lump of hydrogen and helium (we call this 'lump' a molecular cloud) and you are willing to wait a sufficiently long time you will see this material condense into new stars. When this condensation occurs, the gas gets hot enough to begin nuclear fusion. This occurs at about 10 million degrees K.

It is important to distinguish between nebulae that are associated with star formation, which is the subject of this section, and nebulae that are associated with the end of a star's life. The way the nebula lights up, so you and I can see it, can be the same among star forming nebulae and end-of-life nebulae. More about the end-of-life nebulae later in this manual.

The hotter star forming clouds are generally emission nebulae. An emission nebulae is one in which the glow that you see is the result of the material that makes up the nebula glowing. It is glowing because it has been 'excited' by the hot stars and emits light. These glowing regions, always red, are called HII (H-two) regions. The red part of M20, the Trifid Nebula, and M8, the Lagoon Nebula are both of this type.

The other nebulae of interest are the reflection nebulae. Here, the light from nearby stars is simply scattered by the nebulous material (such as in the blue portion of the Trifid Nebula). This is the same light scattering process that creates the blue sky. So, while there must be enough stellar light to illuminate this material, there is not enough energy provided by the star(s) to ionize the material. Stars may be forming in a reflection nebula but may not have become energetic enough to excite the surrounding material.

Sometimes associated with star forming regions are the dark nebulae, sometimes called absorption nebulae. Stars may form in or near the dark nebulae and may be hidden from our view by denser parts of the nebula. These are sometimes visible in infrared light. Radiation pressure from stars formed near the dark nebulae may affect their shape, however. There is an Astronomical League program for observing these objects if these are of more interest to you.

It is important to keep in mind that these three nebulae types are distinguished by the density of the material (dark nebulae) or whether the material is excited by the imbedded starlight or if the imbedded starlight is of insufficient energy to excite the material and the starlight is reflected and scattered. All three of these are associated with star-forming regions.

When stellar fusion begins and the star becomes stable we have what is called a ZAMS (Zero Age Main Sequence) star. This is a star that is just born and just taking its place on the main sequence of the HR diagram.

Credit European Southern Observatory

From Wikimedia Commons

The Eagle Nebula includes several star forming areas. Although the protostars are generally not visible (except in the infrared), the nebula is easy to see.

Fortunately, there are a number of stellar nurseries nearby where we can observe newborn stars or stars about to leave the nest. Some of these are in the observing list associated with this program.

Open Clusters – Early Stars

Stars leave the nest in clusters, open clusters more recently. These clusters of stars have some characteristics that astronomers can use and have used to learn about the stars.

- Stars in open clusters are about the same age (young).
- Stars in open clusters are (for practical purposes) the same distance from us
- The stars all formed from the same nebulous material so they are similar in chemical composition
- The stars may be different sizes (masses) and we can use this to understand what happens to high and low mass stars at different phases of their lifetime

Open clusters tend to be young; the stars that comprise the cluster have not had time to move away from their birthplace. Since open clusters have less gravity than globular clusters the component stars are dispersed earlier. That is, the cluster becomes progressively less well defined earlier. The fact that we can observe the cluster indicates that it's young. (Stars in a globular cluster do not disperse as readily – more stars means more gravity, and more gravity keeps the cluster together.) Through a spectral analysis of the stars in an open cluster, astronomers can determine the age of the cluster and thus the age of all the stars in the cluster. More about this later.

(Note that there are some exceptions – old open clusters. M67 is estimated to be 4 billion years old, but what we see as the cluster stars are present because the young stars have moved out and are not currently recognized as part of the cluster.)

The observing list associated with this program includes several young open clusters. There is an Astronomical League program for observing these objects if they are of more interest to you.

The Main Sequence – the Mid-Life of Stars

Stars spend 90% of their lifetime on the main sequence (after being protostars and before becoming red giant stars). You may never have considered the color of main sequence stars, but as was mentioned before, the color (temperature) and luminosity of stars are related. There are red stars that are not on the main sequence, but these are late-life stars and these will be discussed in other sections of this manual.

One issue associated with making observations of stars in each of the color categories – some colors have a large population of example stars and some do not. Let's look at some of the characteristics of the various colors/classes of main sequence stars. It is correct to say that the fraction of the stellar population for the various star classes gets higher as the colors go from O to M.

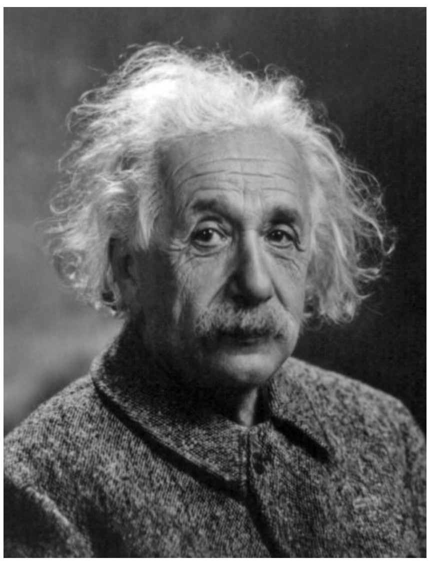
Color	Description	Fraction	Fit in the stellar population
O	Blue	.00003%	While very luminous, a lot of their energy is in the ultraviolet. These stars are very rare. One in 3 million stars are O stars.
B	Blue-white	.12%	More light in the visible range, very bright. About 1 in 800 main sequence stars are B stars.
A	White to blue-white	.60%	Bright and relatively common in the night sky. One star in 160 is an A star.
F	White	2.9%	Very common star in the sky. One in 33.
G	Yellow	7.4%	The Sun is a G star. One in 13 of the main sequence stars are G stars.
K	Orange	12%	About 1 in 8 of the main sequence stars is a K star. Stars get redder as they leave the main sequence. Red Giants are evolved (late life) stars that are not on the main sequence. More about this later.
M	Red	77%	Almost 8 of every 10 main sequence stars is a M star, so these are very common. Stars of this color are often red dwarfs (dim) or red giants (not main sequence stars, but bright).

The column called 'Fraction' represents the fraction of stars that fall within each of the various categories. Note that there are many more M stars than any other color, but they are often very dim, so observers are not as aware of these.

Main sequence stars are burning hydrogen to helium. More accurately, the hydrogen is being converted to helium by nuclear fusion. It turns out that the total mass of the resulting helium is slightly less than the mass of the hydrogen that was fused to create it. Where does the lost mass go? It goes into energy and it is this energy that we see as starlight. Mathematically, this process is based on what is probably the most famous equation in physics:

$E = mc^2$

This simple equation, a creation of Albert Einstein says that energy and mass are the same thing and that mass can be converted into energy and energy can be converted into mass. In the case of stars, including the Sun, mass is being converted to energy at the rate of about 4 million metric tons per second. The astonishing power created by the Sun in this process is almost 400,000,000,000,000,000,000,000,000 watts per second. Of that power, the earth gets about 0.0000000462 % of it or 200,000,000,000,000,000 watts per second. It's a big number, but it only represents a very small fraction of the total Sun's energy output.



The hydrogen is burning in a shell surrounding the helium core of the star. More helium is created by the fusion process in the hydrogen shell. So there will be helium at the center (ash of the hydrogen burning) and hydrogen surrounding this ash furiously burning to create even more helium.

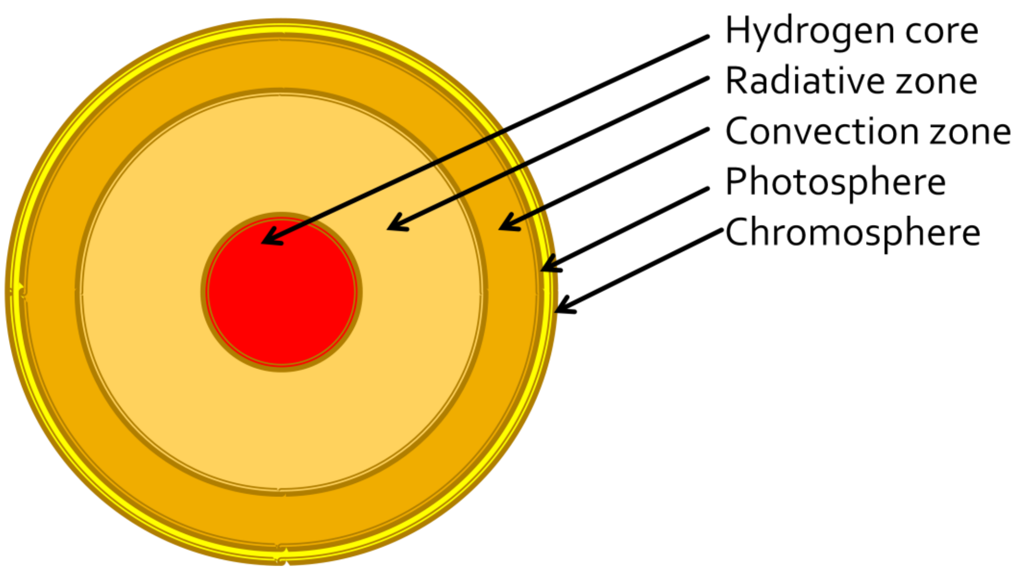
A note about helium. This element was unknown until spectra were taken of the Sun during an eclipse in 1868. The new element discovered at the time was called helium in honor of the Greek name for the Sun, Helios. In the early 1900's helium was found to be naturally occurring on Earth.

Beyond the hydrogen core, there's the radiative zone. In this zone, the energy created in the core or the star is transmitted out via electromagnetic radiation. The final push to the surface of the star is by way of the convection zone. Convection is the method by which the energy from the outside of the radiative zone is carried to the outside of the star. It is similar to the boiling of water on the stove. The water in the pot is being heated from the bottom, but for the heat to permeate the fluid the water boils and the hot water rises to the surface.

Heat is not generated in the radiative or the convection zones; these zones are the ones that carry the energy out from the core of the star to its surface.

There are two more layers of interest, the chromosphere and the photosphere. The photosphere is the location in the star (Sun) at which the 'surface' becomes opaque and it is what we perceive as the surface of the Sun. With hydrogen-alpha telescopes, however, we can see a layer above the photosphere, called the chromosphere.

Schematically, a main sequence star cross section looks like the figure below. All other figures in this manual combine the radiative and the convective zones and omit references to the photosphere and the chromosphere. This is for the sake of simplicity and is not mean to indicate the absence of those layers.



How long a star remains on the main sequence depends on the mass of the star. Low mass stars stay on the main sequence billions of years, and high mass stars stay on the main sequence 'only' millions of years. Our Sun is a low mass main sequence star about halfway through a 10 billion year lifetime.

The observing list in this manual includes examples of each of the various colors of stars.

Low Mass versus High Mass Stars

Everything that happens to a star depends on its mass. Mass is a measure of the inertia of an object when a force is applied. Simply stated, it's something like the weight of material, but independent of a gravitational field. For example, in outer space your body would be weightless, but not massless.

For the purposes of this program stars will be put in one of two categories

- Low mass stars – Stars 8 solar masses or smaller
- High mass stars – Stars greater than 8 solar masses

This division is a bit arbitrary, but will be good enough to describe the differences in the stellar lifetimes of low and high mass stars.

The discussion so far applies to both low and high mass stars. Over 95% of the stars in our galaxy are low mass stars, so the discussion of the evolution of low mass stars describes the process for the vast majority of the stars we can see.

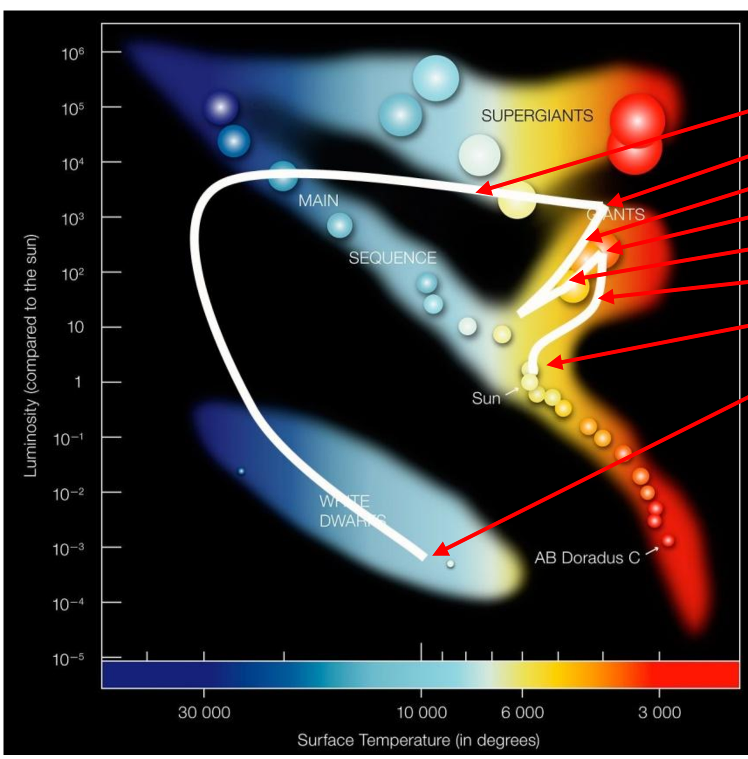
Red Dwarf Stars

Red dwarfs stars represent a special case. These are main sequence stars from about .08 to .5 solar masses and none have left the main sequence. Why? Because their lifetime on the main sequence is longer than the age of the universe. They are, as you might guess, K or M stars. There are lots of these stars, but they are quite dim.

Most of the energy from a red dwarf star is in the infrared.

Low Mass Stars – Leaving the Main Sequence

The Red Giant Branch



Death of a low mass star

- 7-Planetary Nebula
- 6-Red Giant (carbon star)
- 5-Asymptotic Giant Branch
- 3-Red Giant
- 4-Horizontal Branch
- 2-Red Giant Branch
- 1-Main sequence
- 8-White Dwarf

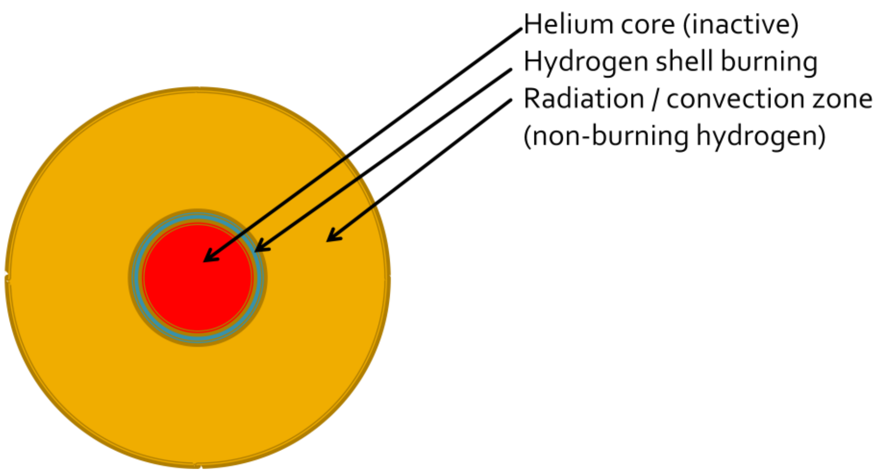
Base Image --
Credit European Southern Observatory

From Wikimedia Commons

The first excursion of low mass stars off the main sequence is along the Red Giant Branch, and stars on this branch are called Red Giant Branch (RGB) stars. The HR diagram shows that the star's color and luminosity have the star moving to the right on the HR diagram and up. (Note that this does not represent the star moving in space, it only means that the color and luminosity of the star are changing during this time and plotting the new, changing, color and luminosity on the HR diagram puts the star in a different 'place'.)

It should be no surprise that as stars move into the Red Giant phase of their lifetime that they get redder. This is what the HR diagram is showing us as the new plotted-point of the star is to the right of the star's position when it was on the main sequence. What's going on in the star at this time?

Stars initially contain a lot of hydrogen, but not an infinite supply. Eventually, the hydrogen gets (mostly) burned up (converted to helium). The stellar core gets smaller and more compressed. The core then, in fact, gets hotter. This is what is happening as the star leaves the main sequence. A cross section of a star on this branch shows the helium ash core surrounded by a burning hydrogen shell. Heat from this active region is carried to the surface by the radiative/convective areas. So, it's the hydrogen shell that's providing the energy for the star; the helium is not yet hot enough to burn.



As the star moves along the RGB path its luminosity increases (plot-point for the star moves up the HR diagram) and it gets cooler per unit area. How is it becoming more luminous as it gets cooler? It is getting bigger as it becomes a red giant. The luminosity during this phase can be several thousand times the luminosity of the main sequence star.

The Sun in about 5 billion years will ascend the Red Giant Branch and its radius will expand to perhaps 1 AU. That is, the Earth may be <u>inside</u> the Sun. If humankind is still around in another 5 billion years they will have had to moved to a cooler planet, perhaps in another planetary system.

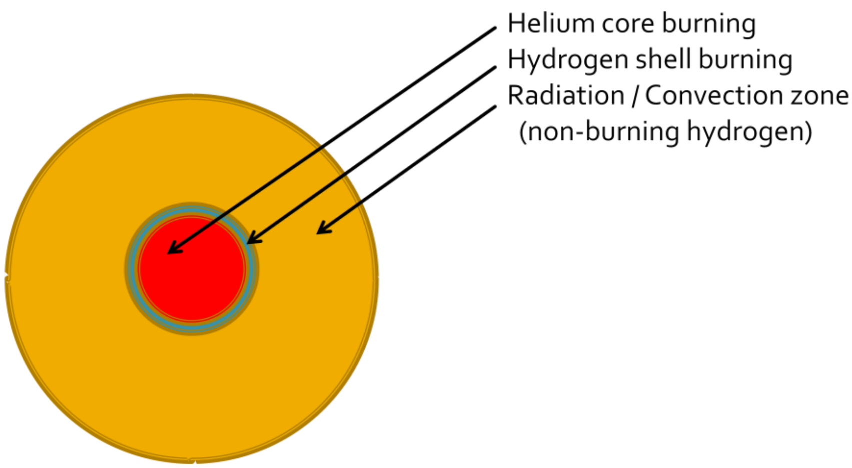
The Horizontal Branch

During the Red Giant Branch the hydrogen burning continues, creating more core helium ash. After some time the core of the star gets hot enough (10^{11} degrees) for helium burning to begin. For stars with lower mass (about 2 solar masses), the helium burning begins with what is called the 'helium flash'. Whether there is or is not a helium flash depends on the state of the matter at the core of the star. At high core densities the core can become degenerate, meaning that classical physics does not apply and that the stellar core is not compressible. The temperature in the core increases rapidly and this is the source of the 'helium flash' event. This is not an observable event, though, because the flash occurs deep inside the star, in the helium core.

For stars with a bit more mass the helium burning begins slowly, but the next stage is the same. Helium core burning is occurring and so is hydrogen shell burning.

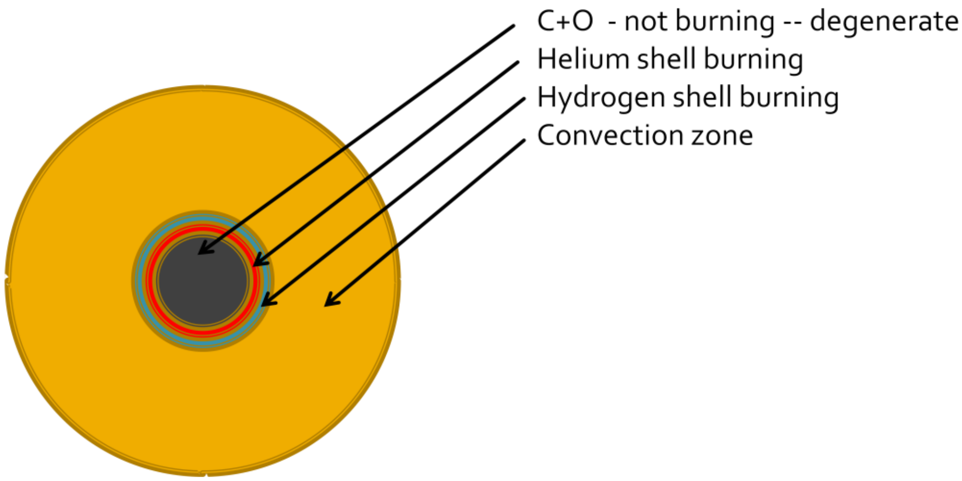
Just because helium burning has begun does not mean that hydrogen burning has ceased. The star is now burning helium at the core and hydrogen in a shell surrounding the helium.

Time on the horizontal branch varies from star to star, of course, but 30 million years is average. The star changes in its appearance by becoming bluer, but retains about the same luminosity. You can see this on the HR diagram.



The Asymptotic Giant Branch – and Carbon Stars

Once helium burning begins, the ash from that process is carbon and oxygen. After a while the core material of the star (helium) is replaced by the ash of the helium burning – carbon and oxygen, and the star looks like the following diagram.



Here, we have both hydrogen and helium shell burning around a non-burning carbon and oxygen core. Gravity acts on the core to shrink its size and the still burning hydrogen and helium layers get hotter.

When that happens, the outer layers of the star expand and a second red giant phase begins. This phase is called the Asymptotic Giant Branch phase and the path (on the HR diagram) almost re-traces the path along the horizontal branch, but with the star moving up and to the right of the HR diagram.

Along the way interesting things can happen. This star maintains a convection zone which carries the heat from the hydrogen and helium shell burning, and in the process can carry to the outside of the star some of the material from the carbon-oxygen core. This is called the 'dredge up' process and creates stars that are called 'carbon stars'. A spectroscopic analysis of the stars shows that there is considerable carbon in the outer layers of the star and the only way the carbon can get there is for it to be carried to the outside of the star by the convection.

A carbon star is a beautiful object to observe. These stars are usually vary in brightness and at their dimmest can look bright red. Hind's Crimson Star (R Leporis) (2700 degrees K) is one example of a bright red carbon star and a delight to see in a small telescope. When we talked about the color scale of main sequence stars the reddest star is a M class star. The carbon stars are often, but not always, redder than that, and the very red ones have their own color class, C.

Another carbon star in our list is called 'La Superba' (Y CVn, Y Canes Venatici).

There is an Astronomical League program for observing carbon stars if these are of more interest to you.

At the end of the star's travel up the AGB, it becomes a Red Giant (for the second time) and may be brighter and larger than it was during the initial red giant phase. This is because the hydrogen and helium shell burning is proceeding at a furious pace as the carbon/oxygen core continues to shrink.

The Planetary Nebula / White Dwarf Phases

A low mass star never gets hot enough to burn the carbon/oxygen core. (High mass stars do get hot enough, and this will be discussed in subsequent sections.) So, what happens instead? Even though the core does not get hot enough to initiate burning the core *does* get hot enough to cause the core to become degenerate. When the core is degenerate, it cannot be compressed any further. Helium burning continues, though, and produces more core carbon/oxygen.

M57 – Ring Nebula
With white dwarf 'star'
Credit –
Hubble Space Telescope
From Wikimedia Commons

The thickness of the helium shell shrinks, becomes unstable, and is the cause of numerous thermal pulses. These pulses start to blow off the outer layers of the star. In a few million years this material surrounds the carbon/oxygen core (not burning). In fact, at this point, the object ceases to be a star (insofar as we define a star as an object that is fusing chemical elements to create new chemical elements).

The stellar remnant, now called a white dwarf, moves to the left of the HR diagram and ultimately circles around to the bottom right of the diagram, becoming a cool glowing object.

On its way, the stellar remnant radiates mostly in the UV (ultraviolet) and this radiation excites the recently (in astronomical time) ejected stellar material, which then glows as a planetary nebula. There are many famous examples of these in the sky. When you look at a planetary nebula, you are seeing an object that is less than about 60,000 years old – planetary nebulae exist no longer than this because they expand and the white dwarf that powers them cools.

The Death of a Low Mass Star

The white dwarf is no longer burning; it is only glowing from the left-over heat from the final helium / hydrogen burning during the AGB phase. This cannot go on forever, and it doesn't. The white dwarf cools and becomes a black dwarf, never to be seen again. None of these can be seen, of course, and none may *exist*. It takes a long time for the white dwarf to cool enough to be called a 'black dwarf' and the universe may not be old enough for that to have happened.

There is an upper limit on the size of a white dwarf – that upper limit is 1.4 solar masses. More about that in the next section.

Do not confuse these with black holes – the remains of a high mass star (this is discussed later) – or with brown dwarfs – very low mass stars that never became 'real' stars.

A Low Mass Nova, and a Low Mass Supernova?

As we will see, high mass stars often end their lives as a spectacular supernova and, as we have discussed, low mass stars end their lives as white dwarfs. There is an exception to the end-of-life story for low mass stars, though, and this exception involves low mass stars that are part of a close binary system. (By the way, the word 'nova' means 'new star' which is what they were believed to be by early observers.)

In a close binary system (double star), the white dwarf and its companion orbit around the center of mass for the system. More generally it is true that any pair of objects that are gravitationally bound orbit around their combined center of mass. The earth and the moon do this, and the position of the earth wobbles a bit as a result.

If the white dwarf and its companion are close enough, the white dwarf may steal material away from its companion. This material is usually hydrogen and helium because that is the material nearest the outside of the star and the material that is the least tightly bound to the star. There is a bit of physics that has to be satisfied for this to take place – involving the distance between the stars and the mass of the companion star, but it is not difficult to understand in a general sense how this could happen.

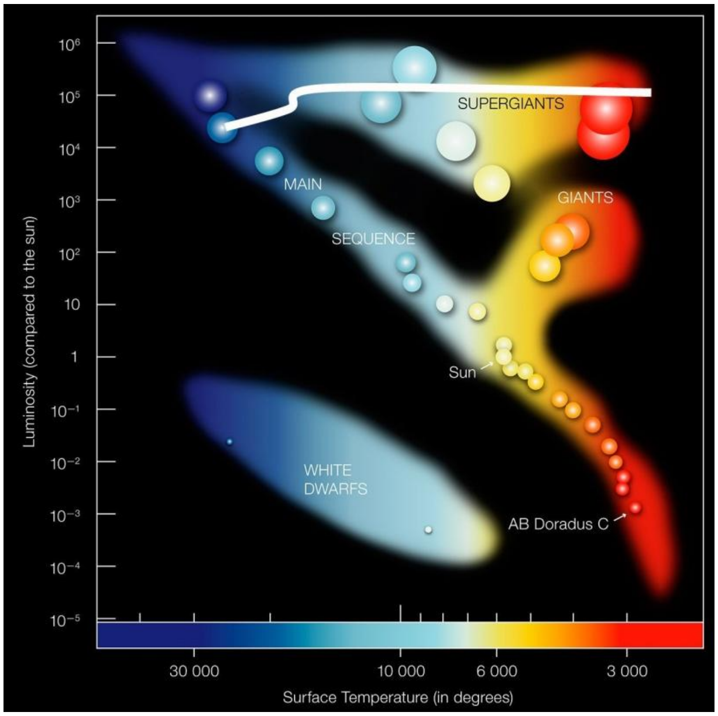
The material from the companion star spirals into the white dwarf and an accretion disk of material forms. When enough new material builds up on the outside of the white dwarf it can re-ignite and the 'stolen' hydrogen can start fusing into helium. It is as though the white dwarf is brought back to life. White dwarfs are dim, so when this happens its luminosity can increase by a factor of ten thousand or so and it can remain that bright for about a month. This is a short-term event, and one of the other effects of the burning is to blow away the remaining material in the accretion disk.

This event is called a 'nova', to differentiate it from a 'supernova' (in which the object self-destructs). After a couple of months the fusion stops and the object returns to its initial quiescent white dwarf state. This process can repeat itself. If the white dwarf accretes more material from its companion there can be another event, and this can go on for quite some time. U Geminorum is an example of one of these recurrent nova stars and any star that is of the 'U Geminorium' type has these same characteristics. U Gem is not on the observing list for this program because it sits at about 15th magnitude during its quiet period (and it would be require a larger telescope to see it at all). At outburst, it jumps to 9th magnitude and would be easily visible in small amateur telescopes.

That's not all… a white dwarf in a binary system can become a supernova under very special circumstances. There is a physical limit on the size of a white dwarf. That limit was discovered by Subrahmanyan Chandrasekhar, and the limit is 1.4 solar masses. The carbon-oxygen material that comprises a white dwarf is degenerate, meaning that it cannot be packed more tightly than it is; it's incompressible. If the amount of material in the white dwarf exceeds 1.4 solar masses the system becomes unstable. So, for example, if the white dwarf was just under 1.4 solar masses and was, therefore, stable, but was accreting material from a companion star it could come to exceed the Chandrasekhar limit, become unstable, and explode as a supernova. This one-time event, called carbon detonation, destroys the structure of the white dwarf. These supernovae are called Type Ia.

These types of supernovae are important to astronomers because they know the mass of the object that created the supernova. Since the event is based on the principle that the star becomes unstable at 1.4 solar masses, this represents the mass of the object that created the supernova. Knowing this, the brightness of the object can be estimated and this kind of supernova can be used as a 'standard candle'. Here's how. If we know the intrinsic brightness of an object and we know how bright the object *appears* to be when we see it, we can use the inverse square law to calculate its distance. So when this type of supernova occurs in a far-off galaxy it gives us yet another way to determine the distance to that galaxy.

High Mass Stars – Leaving the Main Sequence



Base Image --
Credit European Southern Observatory

From Wikimedia Commons

A high mass star is more massive than 8 Suns. Astronomers say that it is > 8 solar masses. High mass stars leave the main sequence and move into late life in a way that is significantly different from low mass stars. The end-of-life of a high mass star is very different too – often a high mass star ends its life as a supernova.

You can think of high mass stars as belonging to a group of stars that live fast and die young. They burn through their hydrogen very quickly and have a short life on the main sequence. Compare the lifetime of our Sun, approximately 10 billion years, with the lifetime of a high mass star, approximately 20 million years. Our Sun is on the main sequence 500 times as long as a high mass star.

This is counter-intuitive. It is easy to think that a star with a lot more material to burn is going to take longer to burn through that material than a low-mass star. The opposite is true; the high mass star burns its hydrogen at a furious rate and ends its life sooner than the low mass star.

Generally, a high mass star will go through many more fusion cycles than a low mass star. While a low mass star will fuse hydrogen to helium and helium to carbon & oxygen, a high mass star will continue working its way through the periodic table to much heavier elements. The final stage of a high mass star is a supernova (Type IIa) and, perhaps, a black hole.

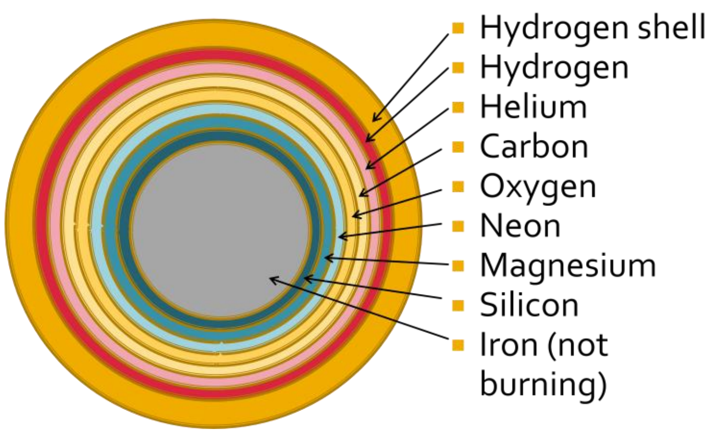
Leaving the Main Sequence

After primary hydrogen fusion has ceased to be the main power source for a high mass star it will leave the main sequence and become a red supergiant (Betelgeuse is an example of a red supergiant). The evolution of high mass stars happens so quickly that it hardly gets out the door before the helium left over from hydrogen fusion starts burning. Changes in the star occur rapidly now.

Once an element in the star is 'burned' the next stage in the burning begins with the ash of the previous stage. The lifetime of a high mass star was stated earlier as 10 million years. This interval represents an estimate of the lifetime of the star on the main sequence, burning hydrogen to helium. As the high mass star leaves the main sequence, this new helium burning phase may last only 10% of the main sequence time. That is, the helium burning phase takes only 1 million years.

Burning gets more fast and furious after this. The carbon left over from the helium burning phase is consumed in only 1000 years and the oxygen in one year. By the time silicon burning takes place, the phase time is down to 1 day. The burning time for these heavier elements (the 'metals') is rounding error in the 10 million year stellar lifetime.

A highly evolved high mass star looks like this –



Some astronomers refer to this stage of stellar evolution as the 'onion' because there are so many coexisting layers to the core of the star.

Supernova

A highly evolved high mass star reaches the end of its ability to fuse elements into heavier ones once the iron core appears. Iron cannot be fused to form heavier elements and give off energy in the process.

If this is true (which it is), how are elements that are heavier than iron created? The answer is that they are created in a supernova by a process called neutron capture. This is not an observable process.

In its highly evolved state something has to happen, and that something is spectacular. Gravity becomes the dominate force on the star and the star implodes, the stellar core disintegrates then rebounds. The iron core consists of degenerate neutrons, and these neutrons cannot be compressed further without obliging more than one electron to occupy the same space, something that physics does not allow. The rebound blows away the outer layers of the star and it is this event that we see as a supernova.

While we cannot guarantee a supernova for you to observe as part of this program, we can point to supernova remnants in the sky. The Crab Nebula (M1) and the Veil Nebula (several NGC objects) are two supernova remnants that are visible in amateur telescopes.

The remnant consists of interstellar gas that has been heated up by the impact of the exploding material (shock wave) from the supernova. SN 1987A, a supernova that appeared in the Large Magellanic Cloud created a well observed supernova remnant (for observers with access to a view of the LMC).

Veil Nebula – Supernova Remnant 2000 ly
Credit –
John Lanoue
From Wikimedia Commons
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Interestingly, supernovae are so bright that the observed brightness was used as an argument *against* galaxies outside the Milky Way. In the days before it was determined that galaxies existed outside the Milky Way it was thought that supernovae were too bright to be something that existed outside our galaxy. Edwin Hubble settled the issue with his work on the Andromeda Galaxy. This story is well told in the book, *The Day We Found the Universe*, by Marcia Bartusiak.

A supernova is exceedingly powerful. A supernova has the energy equivalent of our Sun in its whole lifetime multiplied by 100. The core collapse supernova is a Type II supernova. If scientists look at the spectrum of a Type II supernova, they see evidence of hydrogen; this is, in fact, what identifies a Type II supernova.

Variable Stars

When a star leaves the main sequence, it may enter an area of the HR diagram that we call an 'instability strip' or an 'instability region'. When the star is in this area of the diagram it will become a variable star, one that varies in brightness over time.

There is an excellent program within the Astronomical League on variable stars which goes into this subject in more detail. Many amateurs spend a large part of their observing career on variable stars, have a lot of fun in the process, and contribute to science. They estimate the brightness of the stars and report those estimations to the American Association of Variable Star Observers (AAVSO). The organization's web site is AAVSO.org.

There are variable stars that are not intrinsic variables. That is, the star is not intrinsically varying in brightness, it is be occulted by a companion star or a companion dust cloud. This does not represent a step along the path of stellar evolution, but it *is* interesting. Observing these eclipsing variables is a lot of fun. Some eclipsing variable cycles can be observed in one night. Algol and Beta Lyr are both eclipsing variables.

Intrinsic variable stars are ones that change brightness because the star is pulsating. The size and the temperature change in such a way that we see its brightness change. The categorization of variable stars is complicated and it would be easy to spend a considerable amount of time developing an understanding of these categories.

First, let's look at the naming of variable stars. It is somewhat complicated, but variable stars are usually named with a letter and a three-letter abbreviation of the constellation name. Examples:

R Lyr – The star named 'R' is, curiously, the first variable in the constellation. You have Friedrich Argelander to thank for this designation. The next star is S Lyr, and when the names get to Z, they then have two letters and look like the following

RR Lyr
RT Leo
RW Sco
…and so on.

Good enough. The naming of the variable star tells you nothing about the category of the variable, although a 'prototype' variable star may be used. For example RR Lyr is a 'prototype' for a category of a variable star, so a similar star may be called a 'RR Lyr variable'. Some stars already had a name (either a common name or a combination of a Greek letter and a constellation abbreviation) before they were discovered to be variable, so they retain their original name. Examples – Mira, Delta Cyg

For this program we will look at three categories of variable stars, the characteristics of these and some examples. The three types are:

- Cepheid variables
- RR Lyr variables
- Mira Variables

Cepheid Variable Stars

Cepheid (type) variable stars are stars that are variable over a period of a few days. These stars have a very important characteristic – the period (time of the cycle) of the variability and the intrinsic brightness of the star are related. This relationship was discovered by Henrietta Swan Leavitt at Harvard in the early 1900's and it led directly to Edwin Hubble's discovery that the Andromeda Galaxy was outside the Milky Way.

How? Hubble searched the Andromeda Galaxy for Cepheid variable stars. If he could find one, and if he could measure the period of variability, he would know the intrinsic brightness of the star. All that was necessary now was to use the inverse square law ($1/r^2$) to compute the distance to the star, and thus to the galaxy (1925).

The Cepheid variable stars have moved off the main sequence on their way to becoming a red giant. Classic Cepheid stars are higher mass stars (4 to 20 solar masses) and Type II Cepheid variables are low mass stars (perhaps .5 solar masses).

RR Lyra Variable Stars

These low mass stars have completed the red giant branch of the HR diagram and are on the 'horizontal branch'. They usually show up as color class 'A', but sometimes show up as class 'F' stars. They are dim and small, only about .5 solar masses and are old, metal poor (no elements past helium) stars. They are often associated with globular clusters, and have very short periods (less than one day).

Mira Variable Stars

Mira stars are red giants (which began as low mass stars), with a temperature less than 3,800 K, but with a mass < 2 solar masses. They have a long period of variability, often 800 to 1000 days and are very luminous. These late life stars are near the end of the asymptotic giant branch in evolution and are throwing off their outer layers (which accounts for their variability) on the way to becoming a planetary nebula.

The Mira variables are very popular with amateurs because they are bright and they have slow, long term variability.

Determining the Age of Globular Clusters

Related to this subject is the ability of astronomers to determine the age of globular star clusters based on their understanding of stellar evolution. Here is how this works.

Astronomers assume, with good reason, that stars in a cluster began their lifetime on the main sequence at about the same time. The higher mass members of the cluster will begin moving off the main sequence earlier (remember 'live fast and die young'). So the stars that have reached the 'turnoff point' (that is, started to turn off of the main sequence) can have their age estimated by our understanding of stellar evolution. Since all stars in the cluster are the same age, more or less, the age of the stars turning off the main sequence determines the age of the cluster.

As time goes on, the lower mass stars will begin to leave the main sequence as they age. These clusters constitute a laboratory for astronomers, including you, to see in one place stars of the same age, but different mass.

There is one mystery, though. All of the high mass stars should turn off the main sequence at about the same time, but some do not. These renegade stars are called 'blue stragglers'. They are on the main sequence later than they should. The accepted explanation for this, for now, is that these stars represent the merging of two lower mass stars; they were not born as high mass stars. They may be two lower mass stars that happened to merge due to a chance passing or they may be two stars that formed a binary, a double star, and later merged.

References

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- *Astronomy Today* (textbook) – Chaisson & McMillan
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- *The Brightest Stars* – Fred Schaaf
- *The Hundred Greatest Stars* – James B. Kaler
- www.jdso.org – Journal of Double Star Observations

Observing Stellar Evolution – Observation form

Object	Date	Time	Obs Site Lat/long	Telescope	Magnifi-cation	Description