The Star Cycle — Student Guide

INTRODUCTION

A star has a cycle similar to a life cycle of a plant, the water cycle, nitrogen cycle, or the Kreb's cycle. What does the word cycle mean to you? A bicycle has wheels that spin around and around. The life cycle of a plant is made up of a seed that turns into a seedling which, in turn, becomes a mature plant that produces seeds and then dies. But then the new seeds will grow into new plants, and the cycle goes on and on. The water cycle starts out with a drop of water falling from a cloud. Where does the water go? A star is born from a cloud of interstellar gases. The star matures, grows old, and either explodes or slowly dies out. The matter left behind by dying stars is used by new stars. The time required to reach maturity ranges from 10,000 years for a fast-burning blue star to 2,000,000 years for a star like our sun.

The Star Cycle chart shows stars in each of the various stages that comprise a complete star cycle. An explanation of each of these stages is listed below, following the glossary. (NOTE: All of the bolded words in the text can be found in the glossary.) Worksheets and activities are also included with this guide. By the time you complete the worksheets included with this booklet you should be able to identify the various stages of a star's cycle and the order in which they occur.

GLOSSARY

Absolute magnitude — A measurement of the actual brightness of a star. The absolute magnitude of a star is defined as the apparent magnitude it would have if it were located at a distance of exactly 10 **parsecs** from Earth.

Apparent magnitude — A measure of the brightness of a star as seen from Earth. Originally the brightest star seen was 1st magnitude, dimmer stars 2nd, 3rd, etc. Because of this the magnitude scale is an **inverse** scale. The brighter the star, the lower the numbers.

Binary star system — Two stars that revolve around a common center of gravity.

Black dwarf — A possible final stage of a star, during which the star is non-luminous and has no remaining energy.

Black hole — An object with gravity so strong that the escape velocity is greater than the speed of light.

Brown dwarf — A starlike object that is not large enough to trigger nuclear reactions (hydrogen burning) in its core.

Carbon star — A dying star (usually either a red giant or a supergiant) displaying prominent absorption bands of carbon materials. Carbon stars are the primary way carbon is dispersed into interstellar space.

Constellation — A group of stars in a recognizable shape, often named for an animal, person, god or other object.

Dark nebula (pl. — dark nebulae) — Where protostars are often formed; a cloud of interstellar gas and dust that blocks the light of stars and other objects behind it.

Hertzsprung-Russell (H-R) diagram — A chart showing the correlation between absolute magnitude (or luminosity) of stars and their temperature. An H-R diagram can be found on page S3 of this guide.

Luminosity (L) — A measurement of the electromagnetic radiation (energy) emitted by a star.

Main sequence star — A mature star. On an H-R diagram, these stars are on the main sequence due to their luminosity and temperature.

Nebula (pl. nebulae) — see **Planetary nebula**

Neutron star — An extremely dense and compact star that has collapsed under gravity and is comprised primarily of neutrons; the star matter is also known as "neutronium."

Nuclear fusion — When nuclear fusion occurs, four nuclei of hydrogen fuse to form one helium nucleus and the rest is given off as energy (thermonuclear energy keeps a star hot and glowing).

Parsec — A unit of distance equal to 3.26 light years.

Planetary nebula (pl. planetary nebulae) — Luminous gas ejected by a dying, low-mass star.

Protostar — A star in the early stages of formation, before nuclear reactions begin.
Pulsar — A stellar object (usually a neutron star) that emits pulsating radio waves on a regular basis.
Red dwarf — A small main sequence star that barely meets the requirements for fusion to take place; a red dwarf has a low mass, is relatively cool, has low luminosity and burns for a very long time.
Red giant — A very large late-stage star that has high luminosity and a low temperature.
Solar mass — An astronomical unit of mass equal to the mass of the Sun.
Supergiant — An extremely large and luminous star.
Supernova (pl. — supernovae) — A massive star that becomes extremely bright for a brief period of time due to uncontrolled nuclear reactions.
White dwarf — A dying star that has lost most of its mass due to burning of all nuclear fuel; these stars are approximately the same size as Earth.

BACKGROUND INFORMATION

1. HOW ARE STARS BORN?

Dark Nebulae (#19 on the black line key; note that there are several nebulae shown in different locations on the chart; hence #19 appears several times on the black line key)
Stars are born in cold clouds of interstellar gas and dust that are abundantly strewn throughout the universe. Interstellar dust and gas are the raw materials from which stars are formed. In response to some occurrence, such as a **supernova** or some type of interstellar disturbance, an interstellar cloud begins to contract due to gravity. Before it contracts the cloud is relatively cold (10° K). Its atoms are moving slowly, providing no internal pressure. The cloud starts to close in on itself, contracting due to gravity, until it becomes a single **protostar** or a cluster of protostars. An interstellar nursery consists of a cluster of protostars that are the same age but will be of different masses.

2. WHEN DO STARS BEGIN TO SHINE AND WHAT MAKES THEM SHINE?

a. Protostars (#3 on the black line key)
Protostars form in cold, dark nebulae and can evolve to become young **main sequence stars**. Protostars are created by gravity acting on cold clouds of interstellar dust and gas. More dense portions of the cloud contract under their own weight and form clumps called protostars.

An amazing discovery made possible by the Hubble Space Telescope was the existence of EGGs (evaporating gaseous globules). These globules, which exist at the tips of giant gas and dust pillars, are being eroded away by ultraviolet light from nearby stars. As a result, the protostars inside the nebula stop growing, as there is no more interstellar gas and dust nearby for the protostars to attract (Cowen 1995).

LOOK AT THE CHART; can you see the pillar of gas by the newborn star (#19 on the black line key, above #1 on the left hand side of the chart)? The intense radiation of stars eroded the column of gas into its present shape. A protostar continues to shrink until its temperature at the center reaches a few million degrees K. Hydrogen begins to burn at this temperature. Enough energy is released to stop the internal contraction, and a stable new star is born.

It takes a shorter amount of time for a larger mass star to get to the main sequence than for a low mass star. A protostar that is of great mass develops faster than a lower mass protostar. It takes between 10,000 years for a massive protostar (15 **solar masses**) to make it to the main sequence and 2,000,000 years for a 1 solar mass star like our Sun. And, this newly formed star has only just reached maturity!

b. Brown Dwarfs
These protostars never gain enough mass to reach the required pressure and density to ignite. A brown dwarf is a smoldering ember.

3. STAR LIFE AND AGING

Each protostar that reaches hydrogen fusion requirements will end up somewhere on the **main sequence** (#15 on the black line key), depending on its mass and temperature.

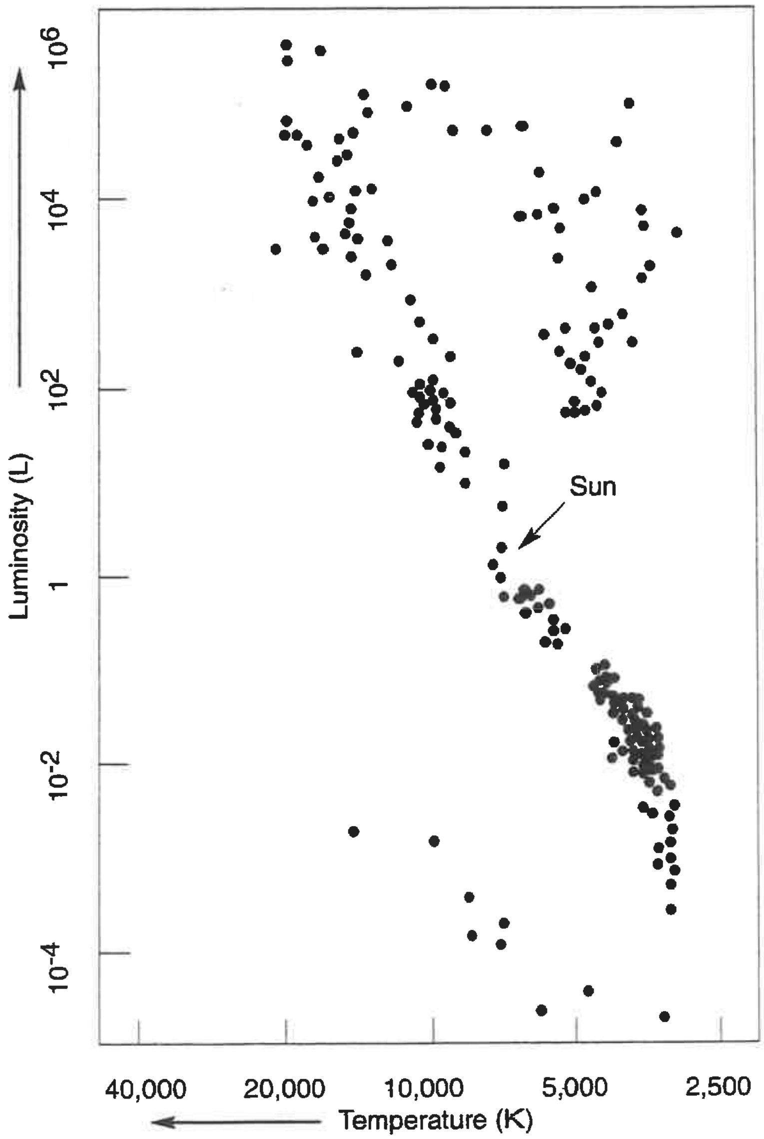
a. Main Sequence Stars

All main sequence stars were once protostars. The main sequence stars represent all stars that are hydrogen burning. The main sequence stars form a diagonal band from the upper left (hot and bright) to the lower right (cool and faint) on the H-R diagram below. The H-R diagram is the plot of the absolute magnitude of stars versus their surface temperature.

1. Nuclear Fusion of Hydrogen

This is the process by which all protostars become main sequence stars. Thermonuclear energy is what keeps a star hot and glowing. Scientists look at our star, the Sun, to understand the process of nuclear fusion. The temperature on the Sun's surface is approximately 5750° Kelvin. At the center of the Sun the temperature is 15 million degrees Kelvin. At temperatures this high there is enough energy to fuse the nuclei of hydrogen molecules together. When nuclear fusion occurs, four nuclei of hydrogen fuse to form one helium nucleus. The weight of the helium nucleus is slightly less than the sum of the four hydrogen nuclei. The difference in mass is converted to energy, as proposed by Albert Einstein in his theory of relativity ($e=mc^2$). How much energy is given off? If .01 grams of hydrogen is converted to helium, there is enough energy to provide your home with electricity for 2,000 years. Nuclear fusion will keep our Sun burning for another 4-1/2 billion years! Not bad for middle age!

LOOK AT THE CHART; the colored stars on the diagonal (#15 on the black line key) represent the main sequence stars. The stars are arranged on the chart based on their temperature and luminosity. These stars represent the data points that comprise the large diagonal band on an H-R diagram. On the chart the size differences of the main sequence stars are exaggerated. However, in the core hydrogen burning main sequence stars, the more massive stars will be hotter, more blue and brighter, so there is a steady progression in size as well as in luminosity and surface temperatures.



LOOK AT THE CHART; on the X axis is a temperature scale. Notice the direction of the temperature scale. Toward which direction on the scale (right or left) would there be an increase in temperature? On the Y axis is a luminosity scale. A red star on the main sequence has a surface temperature of 3000° K and a luminosity of $10^{-3} L_{\odot}$. Look at the blue stars on the main sequence. What is their approximate surface temperature and luminosity? Note that these same scales appear on the H-R Diagram, on the previous page.

LOOK AT THE CHART; study the graph in the lower right corner (#18 on the black line key). This is how scientists can tell what the surface temperature of a star is. A star that burns blue is much hotter than one that burns red or orange. One difference between stars is their color. The color given off by main sequence stars is directly related to the temperature on the star's surface. The coolest stars have a surface temperature of 3000° K. There is a direct relationship between surface temperature and brightness of a star. There is also a direct relationship between a star's mass and its **luminosity**. From this it follows that there is a relationship between a star's size and its luminosity. The larger the star, the more surface area there is from which to radiate light. This is why the **supergiant** (not a main sequence star) is so luminous, even though it has such a low temperature.

2. **Red Dwarfs**
These small stars on the main sequence have barely met the requirements for fusion to take place. On the H-R diagram in the chart, the red dwarfs are found in the lower right corner. Now that the relationships between temperature, mass, size and luminosity have been established, what can be deduced about the red dwarf stars on the chart? The red stars continue to get smaller toward the bottom right of the chart. Red dwarfs have a low mass and are small in size. Because red dwarfs are low mass and small, they are relatively cool, low-luminosity stars that burn for a very long time. They burn their fuel more slowly. As previously noted, the scale of size used to display the stars on the H-R diagram in the chart is a general reference for you. In fact, the size of the supergiant would be much larger in relation to our Sun, and the white dwarfs at the lower center can be smaller than the Earth. It would be impractical to show the actual scale difference between the star classes. If the scale was correct then many of the white and red dwarfs would not even be visible in relation to the Sun (#16 on the black line key). The supergiant would take up the whole chart!

b. **Red Giants** and Red or Yellow supergiants (#10 on the black line key)
The length of time a star remains a main sequence star depends on its mass and surface temperature. Eventually the core will run out of hydrogen gas and become either a **red giant** or a yellow or red supergiant.

LOOK AT THE CHART; locate the red giant. What surface temperature does it have? What is its luminosity? How can it be so luminous? Answer: Even though a red giant's surface temperature is low, it is very bright due to its incredible size.

1. **Aging Low-Mass Stars and Dredge-Ups** (see Diagram A, on the following page)
When the hydrogen core of a star is all used up, the remaining material in the core will be the helium created by hydrogen fusion. The core is not burning and so gravity causes it to contract. Contraction increases the core temperature. The increased temperature increases an area around the core where hydrogen is burning. This shell of burning hydrogen around a shrinking core of helium continues to expand until it cools to about 3500ºK. It is a red giant. The hydrogen-burning shell forms helium, which adds mass to the helium core. Eventually, the helium core ignites and the star burns as a red giant for about 100 million years. Carbon and oxygen are produced in the core by helium fusion. Finally, the core helium is used up. Contraction ignites the helium shell, which causes the shell of burning helium to expand, pushing out the spent layer of hydrogen and an enormous envelope of hydrogen-rich matter about as large as the orbit of Mars. In its final stages, the low-mass star has become a red supergiant. This will be the fate of our sun in about 5,500,000,000 years. If the star is less than about 8 solar masses (one solar mass = mass of the sun) nuclear fusion stops with the fusion of helium into carbon and oxygen.

The oxygen and carbon from the fusion of helium are produced in the core. Late in the life of a red giant the oxygen and carbon can be dredged up by strong convection currents and brought to the surface of the star. This is called a dredge-up, and occurs several times in the life of the star. When a star has enough carbon on its surface to display strong absorption bands of carbon materials it is termed a **carbon star**.

2. Aging High Mass Stars (see Diagram B below)

If a star begins its life with a mass greater than 8 solar masses fusion does not stop with helium. Once the helium in the core has all been changed to carbon and oxygen the core again contracts. It has enough mass to generate enough energy from the increasing pressure to begin the fusion of the carbon and oxygen into neon, magnesium silicon and sulfur. The core is now surrounded by a shell of burning helium and an outer shell of burning hydrogen. Eventually the silicon and sulfur that now make up the core ignite to form iron, nickel and other elements of similar atomic weight. The iron that begins to fill the core will not undergo fusion that releases energy, so, no matter how hot it gets, it will not ignite. The burning core producing iron and surrounded by its burning shells of lighter and lighter materials is a red or yellow supergiant. At this stage in its cycle the high mass star can be nearly as large as the orbit of Jupiter (1,500 million km in diameter), though the core and its burning shells are only the size of Earth.

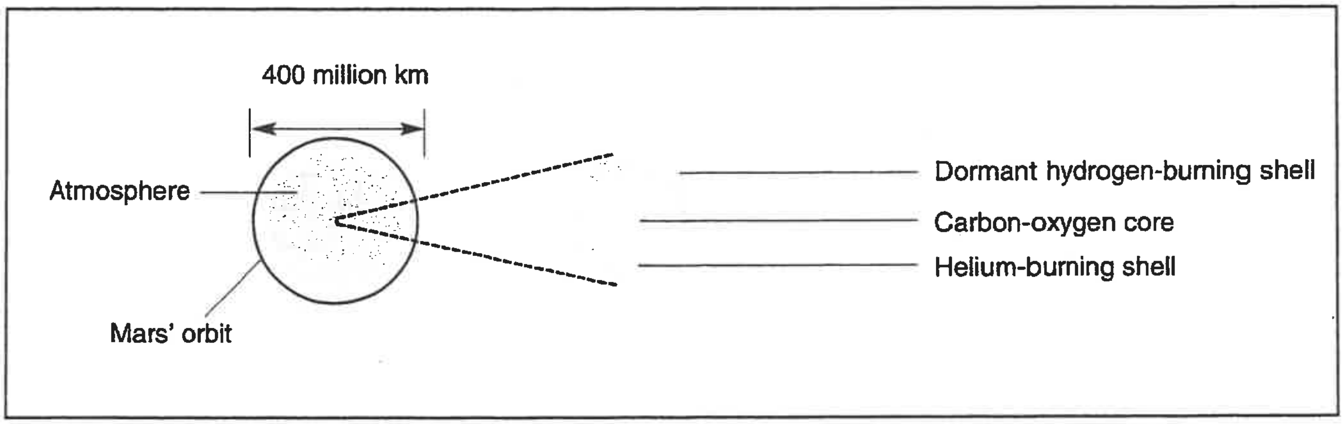


Diagram A: An Aging Low-Mass Star

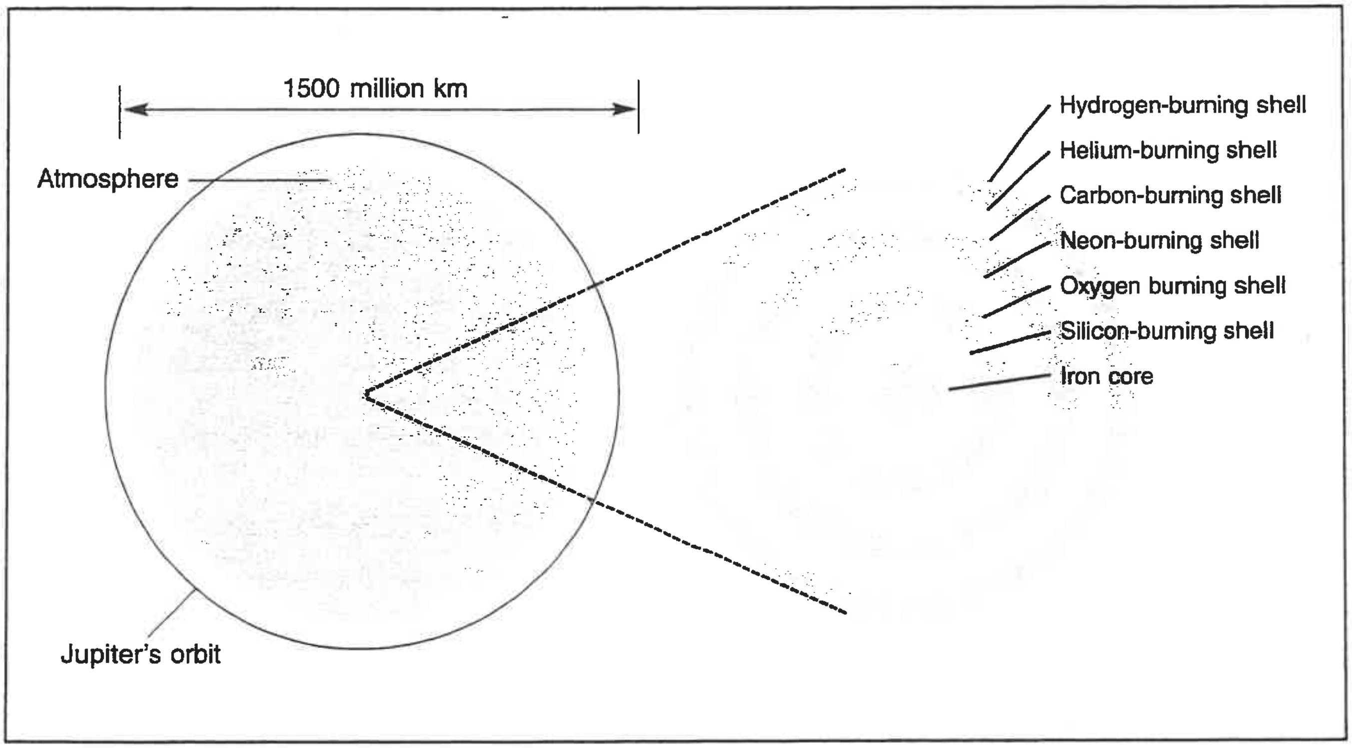


Diagram B: An Aging High-Mass Star

4. DEATH OF STARS (THINK OF IT AS RECYCLING)

The interstellar medium is not only a birth place for stars but a graveyard as well. When star death occurs, the star's elements are given back, enriching space. The way that a star dies depends on how massive it is. Blue-colored massive stars go through their cycle in the fast lane and they go out with a bang. The long-lived red and yellow stars go out more peacefully, gently spitting outer gases away, dying in their sleep.

a. End of a low-mass star

1. **Planetary Nebulae**
The nebula on the chart (#13 on the black line key) is a Helix Nebula much like NGC 7293. Low-mass dying stars often eject their outer layers in the form of planetary nebulae, which can be virtually any shape, size or color. The name "planetary nebula" is deceiving, as these nebulae have nothing to do with planets (19th-century astronomers mistook these nebulae for planets). The word nebula should look familiar to you. It is again interstellar dust. There are several forms that a planetary nebula can take. A low-mass, dying star swells into a red giant before spitting out its outer gases as planetary nebula, gently leaving the shriveled core to become a **white dwarf.** The white dwarf may explode in a nova again before dying if it is in a location where it can acquire mass by capturing inter-stellar dust. A white dwarf is very hot, and produces white light, but is very small. White dwarfs have densities much greater than any terrestrial material. In fact, small white dwarfs are more massive than large white dwarfs.

2. **Black Dwarfs** (#14 on the black line key)
A white dwarf eventually consumes its last bit of helium fuel. It does not have enough mass to start the fusion of carbon and oxygen and turns into a slowly cooling cinder, eventually ending up as a cold, dense and non-luminous black dwarf.

b. End of a High-Mass star

1. **Supernovae** (#1 on the black line key)
Only massive stars create supernovae. The density of the core of the massive dying star reaches 4×10^{17} kg/m^3. At that point, the core can be compressed no more. The unsupported regions surrounding the core rush in towards the core at unbelievable speeds. Enormous increases of pressure and temperature force the material to bounce back out toward the surface. The waves rapidly accelerate as they encounter less and less resistance, eventually becoming shock waves. The shock waves induce explosive nuclear burning ejecting the envelope at speeds in excess of 10 million miles per hour. During this time elements heavier than iron are formed. Once the shock waves reach the star surface, the outer layers begin to lift away explosively, brightening and creating a supernova. A supernova explosion may create a white dwarf, **neutron star** or a **black hole**.

2. **Neutron Stars** and **Pulsars** (#8 on the black line key)
A 25 **solar mass** star may eject 24 solar masses of material and leave behind a corpse called a neutron star. A neutron star is an incredibly compact stellar corpse. A typical neutron star consists of roughly one solar mass compressed to nuclear density within a sphere less than 30 km in diameter. The dead star's gravity is so strong that the speed needed to escape its surface is half the speed of light. A thimbleful of matter from the surface of a neutron star would weigh 100 million tons on Earth. The reason that a neutron star is so heavy is that all protons and electrons convert to neutrons with very little space between them (forming "neutronium"). When a neutron star spins very fast, it creates an intense magnetic field, sending out beams of radio waves from its poles. As these radio waves pass Earth we see a radio flash or pulse; thus the name **pulsar**. As these radio flashes occur, the pulsar in the Crab Nebula (#7 on the black line key) flashes on and off in visible wavelengths.

LOOK AT THE CHART; the pulsar (#8 on the black line key) can be seen within the Crab Nebula.

3. **Black Holes** (#9 on the black line key)
Under certain conditions, a massive star might blow up and leave only interstellar gases behind. Under yet another set of conditions inside the star, a massive burned out core might completely collapse onto itself and create a black hole. When a corpse is too massive (3 solar masses, for example) to become a white dwarf or a neutron star, its burned out matter presses inward with incredible intensity to a density even greater than that of a neutron star. Because of this compression, the escape speed of the stellar corpse exceeds the speed of light. Once 3 solar masses of matter squeeze into a sphere 18 km in diameter, the star literally disappears from sight. Why does it disappear? Because its escape velocity has exceeded the speed of light! However, some of its effects are still observable because its gravity alters the very fabric of space. Because of the black hole's great gravity, it forms a rapidly rotating disk around itself called an accretion disk. As matter falls from the disk into the hole, X-rays are given off and some matter is ejected in the telltale jets that astronomers have detected.

5. APPARENT AND ABSOLUTE MAGNITUDE

Apparent magnitude describes how bright a star appears from the Earth. It is a measure of light energy reaching Earth. **Absolute magnitude** is a measure of the actual brightness of a star. It is defined as the brightness the stars would have to an observer on the Earth if the stars were located a fixed distance (10 **parsecs**) from Earth. Both scales are inverse scales; the greater the number, the less luminous the star. The absolute magnitude of stars ranges from –10, which is the brightest, to +15, which is the dimmest.

But how can you tell whether you are looking at a close, dim star or a distant, bright one? Detailed information about stars comes mainly from the energy they send out into space. Observing closer stars from different points in the Earth's orbit (i.e. at different times of the year) can show their distance. From their distance and their apparent magnitude you can compute their absolute magnitude as there is a direct relationship between absolute magnitude compared to apparent magnitude and the distance a star is from the Earth. Conversely, a star's absolute magnitude can be determined by the period (one to several days) over which it is seen to change in brightness. Once the absolute magnitude is known, the distance can be computed, again using the direct relationship between absolute magnitude compared to apparent magnitude and the distance from the Earth.

LOOK AT THE CHART; the right Y axis shows absolute magnitude. Our Sun is in the middle of the range, showing that it has an average absolute magnitude. The absolute magnitudes on the chart are expressed as **luminosity (L),** a measure of the energy emitted by a light source per second.

6. BINARY STAR SYSTEMS

As many as 40% of the visible stars in the night sky may be binary or multiple star systems. By studying visible binary star systems astronomers and physicists are able to calculate their mass. The center of mass is the center point around which both stars travel in an elliptical orbit. The center of mass is always closer to the more massive star. Through many years of observation by several scientists, visual binary systems were analyzed and the masses of stars calculated. By studying spectra, scientists can study non-visible binary stars as well.

LOOK AT THE CHART; the diagrams on the bottom left (#17 on the black line key) show a binary system. Spectral analysis shows a line shift from stage 1, which shows lighter spectral lines to the left of the darker spectral lines. At stage 2 these lines disappear. At stage 3 they reappear to the right. At stage 4 they seem to disappear again. What makes the spectral lines appear to shift is the position of the orbiting stars around the center of gravity, as they appear from Earth.

Looking at the center of gravity, you can tell that these stars are approximately the same size because they are of equal distance from the center of gravity. If the star on the right in this binary system were more massive, then the center of gravity would be closer to the massive star.

7. INTENSITY VS. COLOR

LOOK AT THE CHART; in the lower right corner (#18 on the black line key) is a graph showing intensity peaks of three different colored stars. We already know that surface temperature is directly related to the color given off by a star. The diagram indicates the temperature, the intensity curve and the color (represented by wavelength). Each color represents a particular wavelength range of that star. First, observe the intensity curve of each star. At the peak of the intensity curve is where the emission of energy is the strongest. The dominant wavelength gives the star its color.

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