

## The Properties of Stars

Early in its history, the universe organized itself into superclusters, clusters of galaxies, galaxies, and stars. We do not know the order in which these various levels of organization formed. What is clear, however, is that about 13.5 billion years ago, the first stars formed. Because only the chemical elements of hydrogen and helium emerged from the Big Bang, the first stars were virtually pure hydrogen and helium. As these stars evolved, they produced additional chemical elements by nuclear reactions deep within their interiors. The explosive deaths of the most massive of these stars distributed these heavier elements throughout the galaxy so that late-generation stars had small but significant amounts of elements heavier than helium. Our sun, which formed 4.6 billion years ago, is one such star.

### *The Sun: An Average Star*

After eons of observing the fiery ball they saw in the daytime sky, humans finally identified it as similar to the pinpoints of light they saw in the night sky. Less than eight-and-a-half minutes away by light travel, the sun is our most available laboratory for the study of stars in general. We are immersed in its radiation. It both nurtures and destroys life on earth. It is of mythic psychological importance to human beings. In the broader cosmological scheme, however, our sun is a fairly typical star. Like the other stars, it is a large sphere of gas with a very hot visible surface that continuously emits tremendous quantities of energy in the form of electromagnetic radiation.

Some important properties of a star are its mass, size, surface temperature, color, and luminosity. The mass of our sun (one solar mass) is about  $2.0 \times 10^{30}$  kilograms. This constitutes about 99.9% of the mass of the entire solar system. The masses of other stars range from about 60 solar masses to about 1/12th solar masses.

The diameter of the visible sphere of the sun is about 870,000 miles. This is over 100 times the diameter of the earth. The largest stars have diameters 1,000 times greater than this, and the smallest active stars are about 1/50th of a solar diameter. Stars no longer generating energy can be even smaller; white dwarfs, for example, are only about the diameter of the earth, and neutron stars are only about 10 miles or so across.

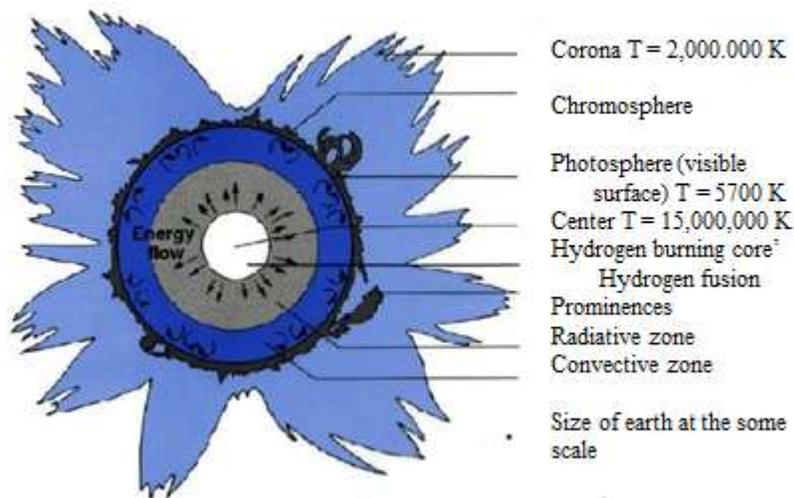
The temperature of the visible surface of the sun is 5,700 K. (K is the symbol for the Kelvin temperature scale. It is an absolute temperature scale, with 0 K being absolute zero. The Kelvin scale is offset from the Celsius scale by 273 degrees. Thus, 5,700 K is 5,973 C.) It is this surface temperature that is responsible for the sun's yellow color. The hottest stars have surface temperatures of about 40,000 K and are bluish in color. Stars with surface temperatures of about 10,000 K are white, and those around 4,000 K are reddish-orange. The coolest stars have surface temperatures of about 3,000 K, which makes them appear deep red in color.

## Properties of the Sun

The Sun Compared with Other Stars		
Property	Solar Value	Stellar Range
Luminosity	$L = 4 \times 10^{26}$ watts	$10^6 L - 10^{-4} L$
Mass	$M = 2 \times 10^{30}$ kilograms	$60 M - 0.085 M$
Size	$R = 7 \times 10^8$ meters	$1000 R - 0.01 R$
Color	Yellow	Red to bluish-white
Surface Temperature	5700 K	3000 K – 45,000 K
Age	4.6 billion years	~0 to 13 billion years

In the table above, L, M, and R refer to the luminosity, mass, and radius of the sun.

## Structure of the Sun



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A property of the sun and the other stars that is closely related to surface temperature and color is that of spectral class. Around the turn of the century, astronomers began classifying stars by their dark-line spectra. Some stars have more pronounced dark lines than do other stars. At first it was not understood why this should be the case, and the stars were simply grouped into classes according to their similarity of appearance. The stars with the most pronounced hydrogen absorption lines were put in class A, those with somewhat less pronounced hydrogen lines, class B, and so on up to the letter Q. Most of these classes were later merged, leaving only classes A, B, F, G, K, M, and O.

Eventually it was realized that the appearance of the dark lines was related to the surface temperature of the star. To adjust the established spectral classes to this new understanding, the letters were rearranged to correspond to a sequence of decreasing surface temperature. From hottest to coolest surface temperatures, the spectral classes are O, B, A, F, G, K, and M. The sun's spectral class is G.

The luminosity, or the energy output per second, of our sun is usually measured in watts. The sun emits energy at a rate of  $4 \times 10^{26}$  watts. The most luminous stars emit about one million times more energy per second than the sun, and the least luminous stars emit only one-ten-thousandth as much.

Other, less conspicuous properties of stars are also of interest to us. Among the most important of these is chemical composition. The sun is composed predominately of hydrogen and helium, with relatively small percentages of the heavier elements. Other stars are also mostly hydrogen and helium, but they have varying amounts of the heavier elements.

Another important property of a star is its internal temperature. The temperature of a star rises with increasing depth beneath the visible surface of the star. At the center of the sun the temperature is about 15 million K. The internal temperature of a star depends on its mass. The more massive a star, the higher the internal temperature required to support it against gravity. The normal range is in the tens of millions of kelvins, with about 10 million kelvins for the lowest-mass stars. The central temperature rises as the star ages, with drastic increases during the final "dying" stages of a star's evolution.

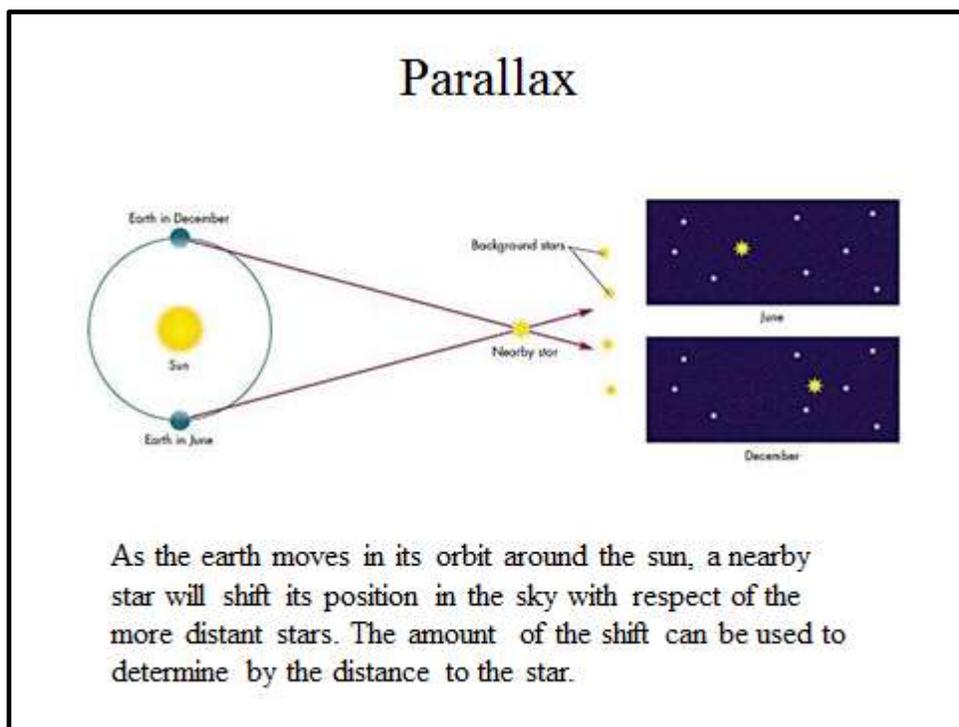
### ***Distance, Apparent Brightness, and Luminosity***

Standing under a clear sky and looking at the universe with the naked human eye, it is easy to believe in the existence of a celestial sphere. Everything seems to be the same distance from us. There is a clue, however, that this is not the case: some stars appear much brighter than others. Perhaps some stars are just intrinsically brighter than others, but the differences in brightness also suggest the possibility that some stars appear brighter because they are closer to us. It was not until the early part of the nineteenth century that distances to stars could be measured. However, the method used today has historical roots dating to the ancient Greek astronomer Aristarchus.

Aristarchus concluded that the earth revolved around the sun. This idea was rejected by most of his contemporaries for what were very legitimate, even scientific, reasons at the time. They argued that if the earth orbited the sun, we would observe

the stars from successively different places throughout the year. This would cause a shift, or parallax, in the apparent position of the near stars with respect to the more-distant ones. Because none of Aristarchus' contemporaries could observe this parallax, the argument that the earth orbits the sun was judged to be incorrect at the time.

Aristarchus realized that if the nearest stars were extremely far from the earth and sun, then parallax, although present, could be so small as to be unnoticed (this was in fact the correct reason, and why parallax was not observed until the nineteenth century with the arrival of more advanced observational tools). Aristarchus' argument was not convincing to his contemporaries, however. No one was willing to accept a model of the universe in which the sun and the planets were bunched together with the stars separated from them by tremendous distances. Why waste all that space?



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By the time of Newton, the theoretical arguments for the motion of the earth around the sun were overwhelming, but observational evidence still was lacking. Throughout the eighteenth century and into the nineteenth century, many astronomers tried unsuccessfully to detect stellar parallax. It was not until 1839 that the first successful observations were made. One of first stars to show parallax was Alpha Centauri, the closest star to us, and therefore the star with the largest parallax angle. Even so, its parallax angle is a mere 0.76 seconds of arc. The geometry of the parallax triangle gives a distance to Alpha Centauri of over 280,000 times the distance between the earth and the sun, or about 4.3 light-years away. It turns out that there is a lot of "wasted space" in the universe after all.

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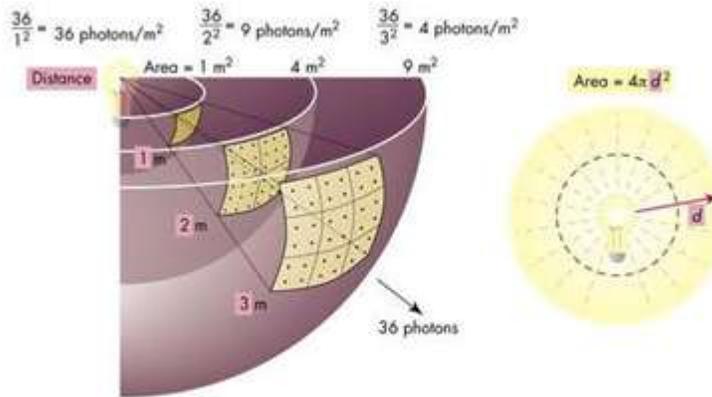
Only a very small percentage of stars are close enough for us to measure their parallax angles accurately. However, with some stellar distances measured, astronomers could now begin to study the luminosities of the stars.

The most obvious differences among the stars in the sky are their apparent brightness. Apparent brightness is determined by how much energy in the form of visible light reaches our eyes per second – the more energy per second, the brighter the star appears. To begin to understand the factors that determine apparent brightness, consider an ordinary light bulb. Think for a moment about what determines how bright a light bulb appears to you.

One factor involved in determining the apparent brightness of any source of light is how much energy it emits per second; that is, its luminosity. For a light bulb, the luminosity is measured in watts, and its value is written right on the bulb. A 100-watt bulb emits twice as much energy per second as a 50-watt bulb, and if both are at the same distance, the 100-watt bulb looks brighter than the 50-watt bulb. The distance between the light source and the observer is the other important factor determining the apparent brightness of an object. As you move farther and farther away from a light bulb, it appears less bright. The bulb's apparent brightness – the amount of energy per second received by your eye – will drop off with the square of the distance. That is, doubling the distance will decrease the amount of energy received per second by a factor of four; tripling the distance will decrease it by a factor of nine; and so on. This precise mathematical relationship among luminosity, distance, and the energy received per second, also known as the inverse-square law, is of great importance to astronomy. Because it is always possible to measure the apparent brightness of a star, its luminosity can be calculated if its distance is known.



## Inverse-Square Law



The luminosity of a star is determined by the number of photons emitted per second. The apparent brightness of a star is determined by the number of photons per  $\text{m}^2$  per second that reach the observer.

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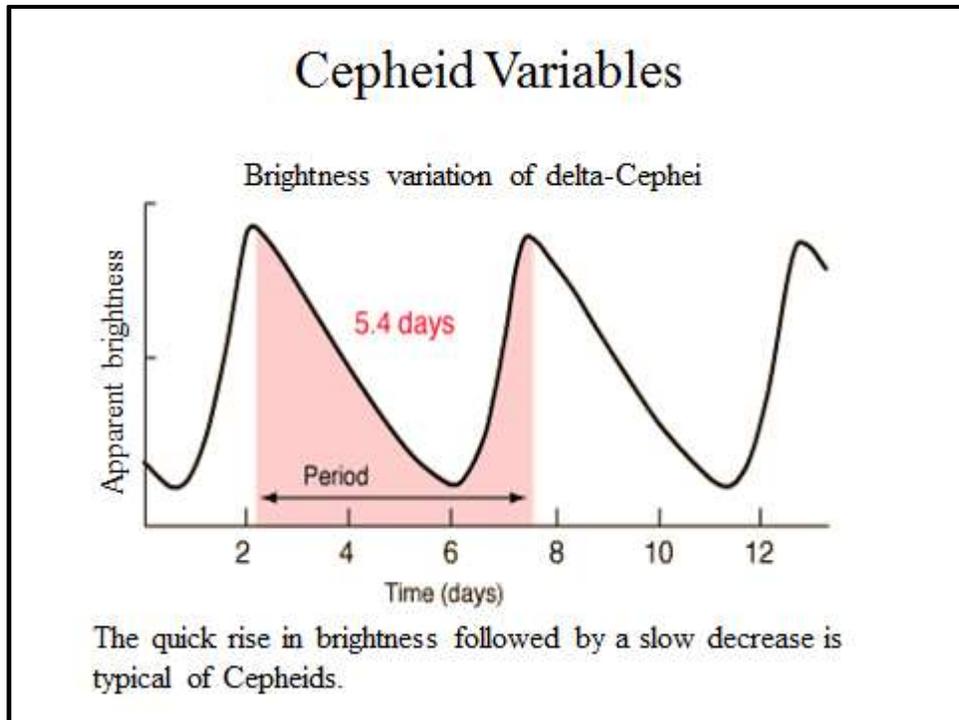
Turning this relationship around, it is possible to calculate the distance to any object whose luminosity and apparent brightness are known. Other than parallax, a technique that only works for very close-by stars, the inverse-square law is the primary way distances to other stars and even galaxies are determined. The inverse-square is the primary tool that has allowed us to determine the scale of the universe.

One of the most important uses of luminosity to determine distance involves Cepheid variable stars. Cepheid variables are large (some 30 to 300 times the diameter of the sun) yellow stars with variable luminosities. The variations in their luminosities are associated with the expansion and contraction of their visible surfaces. These pulsations are very regular and have periods that range from a few days to as much as 100 days. The ratio of maximum luminosity to minimum luminosity can be as low as 1.1 for some to as high as 6 for others. The North Star, Polaris, is an example of a low-amplitude (that is, a low maximum-to-minimum luminosity ratio) Cepheid variable.

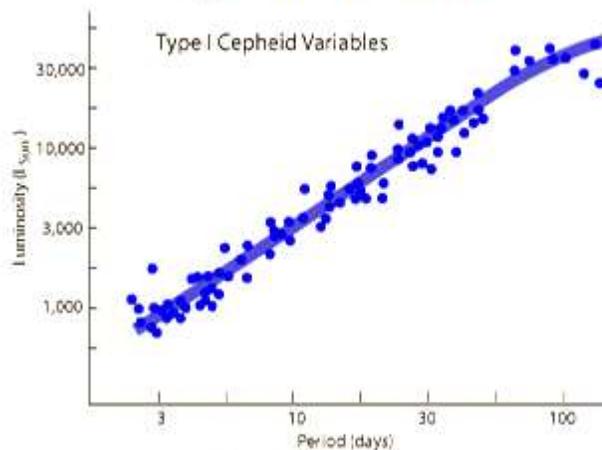
In the early part of this century, astronomer Henrietta Leavitt identified 25 Cepheid variables in the Small Magellanic Cloud (later discovered to be a companion galaxy to the Milky Way). Leavitt determined that the average luminosity of these stars was related to their periods of pulsation: the larger the period, the greater the average luminosity. The period of a Cepheid variable can easily be determined by plotting its apparent brightness over a long-enough time for it to go through several full cycles of variation. The period-luminosity relationship can then be used to determine the luminosity of the Cepheid.

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Because Cepheid variables are giant stars, they are quite luminous and therefore can be observed at great distances. They provide one of the best methods we have for calculating the distances to nearby galaxies. The procedure involves identifying a Cepheid and determining from observation both its period and its average apparent brightness. The period-luminosity relation then can be used to determine its average luminosity. Knowing its average luminosity (how much energy it emits per second) and its average apparent brightness (how much energy we receive per second), its distance can be computed using the inverse-square law. This is a less-direct method for determining distances than is parallax, but it can be applied at much greater distances.



## The Period-Luminosity Relation for Cepheid Variables



The longer the period of variability, the greater the average luminosity of the Cepheid variable.

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### The Hertzsprung-Russell Diagram

The Stefan-Boltzmann law relates the size and temperature of a star to its luminosity. The total energy radiated each second by one square centimeter of an object's surface is equal to a constant (represented by the Greek letter *sigma*,  $\sigma$ ) times the temperature  $T$  in kelvins raised to the fourth power, or  $\sigma T^4$ . If the absolute temperature of an object doubles (increases by a factor of 2), the energy radiated per square centimeter will increase by a factor of 2 raised to the fourth power, or 16 ( $2 \times 2 \times 2 \times 2 = 16$ ). Luminosity is the total energy radiated per second, so the energy radiated by one square centimeter must be multiplied by the total area of the object. Stars are spherical, so their total area is  $4\pi R^2$ . Thus,  $L = 4\pi \sigma R^2 T^4$ .

For the purposes of calculations, it is often convenient to express this equation in terms of solar values.  $L_o = 4\pi \sigma R_o^2 T_o^4$ , where the subscript refers to the sun. Combining the two equations, the general equation for the luminosity of a star can be written as  $L = (R/R_o)^2 (T/T_o)^4 L_o$ . To illustrate this equation, determine the radius of Betelgeuse given that its luminosity is  $1.2 \times 10^5 L_o$  and its surface temperature is 3,100 K:

$$\begin{aligned}
1.2 \times 10^5 L_{\odot} &= (R/R_{\odot})^2 (3100 \text{ K}/5700 \text{ K})^4 L_{\odot} \\
1.2 \times 10^5 &= (R/R_{\odot})^2 (0.087) \\
R^2/R_{\odot}^2 &= 1.38 \times 10^6 \\
R &= 1174 R_{\odot}
\end{aligned}$$

Thus the radius of Betelgeuse is 1,174 times that of the sun. Betelgeuse is a red giant.

In the early part of the twentieth century, the idea occurred independently to the astronomers Ejnar Hertzsprung and Henry N. Russell to plot the luminosities of stars on a vertical axis with their surface temperatures on a horizontal axis. In their honor, such plots are now known as Hertzsprung-Russell diagrams. Because of the Stefan-Boltzmann law, these diagrams also contain information about the sizes of the stars. H-R diagrams will be useful in the next reading, when we discuss stellar evolution.

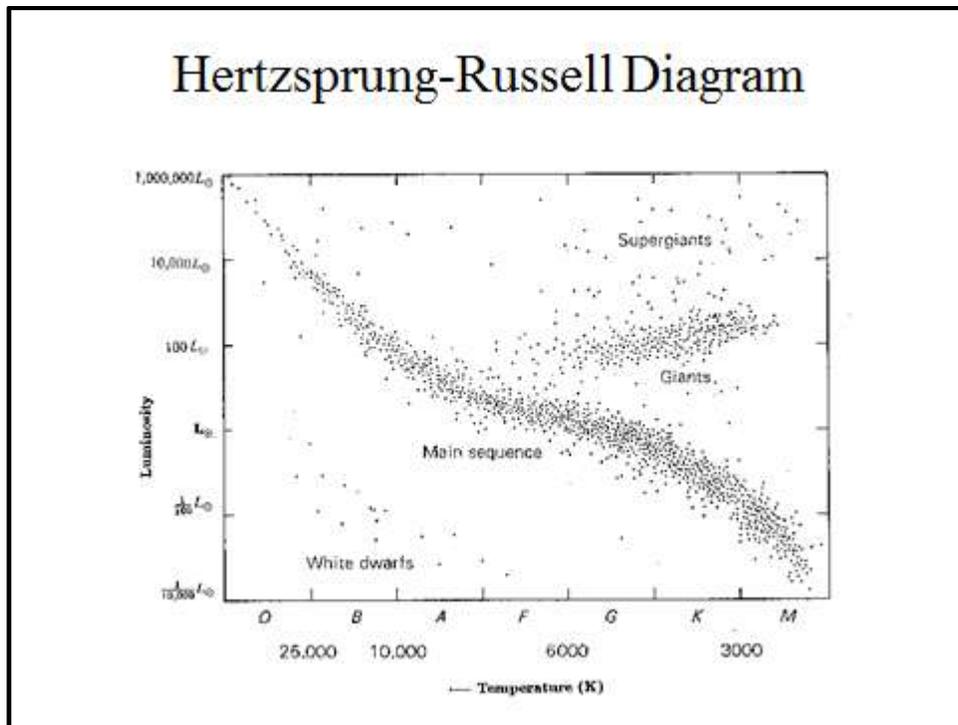
Stars are not scattered evenly over the H-R diagram; instead, they tend to appear in groups. One such group runs from the lower-right-hand corner (cool, low-luminosity stars) to the upper-left-hand corner (hot, high-luminosity stars). This should seem quite reasonable; in general, stars with hotter surfaces might be expected to be more luminous. This diagonal on the diagram is called the main sequence. Our sun is a main-sequence star. Main-sequence stars convert hydrogen into helium in their cores, as we will discuss in more detail in the next reading. Stars are main-sequence stars throughout most of their lifetimes.

When both the mass and the luminosity of a main-sequence star can be determined, it is found that the greater the mass, the greater the luminosity of the star. The more-massive main-sequence stars produce and radiate energy at a greater rate than the less-massive ones, due to their higher densities and core temperatures. This mass-luminosity relationship applies only to main-sequence stars.

Stars not located on the main sequence of the H-R diagram are either protostars (not quite stars yet), dying stars, or dead stars (a star in which nuclear reactions are no longer occurring and therefore, no additional energy is being generated). One such group of stars is located in the center right of the H-R diagram. Stars in this region are much cooler than our sun and typically are red in color. However, they are also much more luminous. In order to be both cooler and more luminous, according to the Stefan-Boltzmann equation, these stars must be much larger. (Do not confuse larger with more massive. Some of these stars are more massive than the sun and some are less massive. However, all are larger in diameter.) This region of the H-R diagram is called the red giant region. We will see in the next unit that these stars are post-main-sequence stars that have consumed all of the hydrogen in their cores, and thus are dying stars.

Some stars are found in a band running across the top of the diagram. These stars have a wide range of surface temperatures but are all extremely luminous, ranging from about 10,000 to 1 million times the luminosity of the sun. These stars are believed to be dying, high-mass stars. They are immense, with the cooler red ones much larger than even the red giants. These stars are called supergiants. Betelgeuse, the reddish shoulder star of the constellation Orion, the one we calculated the radius of earlier, is a supergiant. If its center were at the center of our solar system, its visible surface would extend out beyond the orbit of Mars.

The last region of the H-R diagram we will discuss at this time is in the lower left of the diagram. Stars in this region have temperatures higher than our sun, but much lower luminosities. Using the Stefan-Boltzmann equation, we see that these must be very small stars relative to our sun. Their radii are only about 1/100th that of the sun, or about the size of the earth. They are called white dwarfs and are dead stars radiating away the energy they built up over their active lifetimes. Their surface temperature will slowly decrease. After billions of years they will gradually fade from view as they become too cool to give off visible light.



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H-R diagrams provide astronomers with a tool for examining the life cycles of stars. Protostars begin off the main sequence, move onto it for most of their lifetimes, and then move off again in their dying phases. It is impossible to directly observe this entire process unfold for any one star, given our short human lifespans compared with those of stars. However, by examining at one time a cross-section of the sky's population of stars, H-R diagrams give graphic evidence of the stages of stellar evolution. The evolutionary processes revealed through such examinations are described in the next reading.