In earlier chapters, we have learned a great deal about the general physical properties of stars. As a prelude to this chapter, the ranges of the most important of these stellar properties for as wide a sample of stars as reasonable is summarized in Table 17.1.

Table 17.1. Range of Stellar Properties

<table>
<thead>
<tr>
<th>Stellar Property</th>
<th>Range*</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>10^{-2} to 10^{+2} Msun</td>
</tr>
<tr>
<td>radius</td>
<td>10^{-2} to 10^{+3} Rsun</td>
</tr>
<tr>
<td>mean density</td>
<td>10^{-7} to 10^{+7} rsun</td>
</tr>
<tr>
<td>luminosity</td>
<td>10^{-5} to 10^{+5} Lsun</td>
</tr>
<tr>
<td>surface temperature</td>
<td>10^{+3} to 10^{+5} K</td>
</tr>
<tr>
<td>heavy-element mass abundance**</td>
<td>0.05 to 2.0 Zsun</td>
</tr>
<tr>
<td>age</td>
<td>10^{+4} to 10^{+10} y</td>
</tr>
</tbody>
</table>

* * Solar units: M_{Sun} = 2 \times 10^{+33} g, R_{Sun} = 7 \times 10^{+5} km, L_{Sun} = 4 \times 10^{+33} \text{ erg/s}, Z_{Sun} =
One characteristic that appears in the table and which we have not previously discussed (it was only implied in earlier chapters) is the age of stars. Even up to relatively recent times many have assumed that the lives of stars was beyond the comprehension of humans; and yet now we believe that we do indeed comprehend a great deal about the lives of stars. Stars have definite ages that cover an immense range. In this chapter and the two following chapters we shall consider such questions as how stars are created, what keeps them shining throughout their active lives, and how they end their existences.

17.1. Physical Structure of Stars

The Sun is the astronomer’s basic model for stars. We feel confident that we know the physical laws operating inside the Sun and therefore presumably inside other main-sequence stars. For example, if the Sun emitted radiant energy simply because it is a hot body without any internal source of energy, it should cool at a rate fast enough for us to measure the decrease. But the evidence suggests that the Sun is not cooling significantly; consequently the Sun and other main-sequence stars must have a source of energy deep in the interior that replaces energy radiated away from their surfaces, thereby keeping the deep interior hot.

17.1.1 Interpreting the H-R Diagram, Ages of Stars

The significance of the H-R diagram became clear several decades ago when it was realized that the H-R diagram is a panorama portraying how stars evolve. A star’s position in the diagram is a function of its mass, chemical composition, and current age. There is a physical reason why the points in the diagram are not scattered at random: the natural forces that guide the evolution of stars confine them to portions of the diagram where they can convert matter into radiant energy. For example, the Hertzsprung gap (Figure 13.8) is a region in which there are known to be very few stars; it must therefore be a region through which evolving stars pass quickly. The important point here is that stars do evolve: they are born, age, and eventually die. Thus the stars of our Galaxy are not all the same age as the Galaxy itself, since there are young, middle-aged, and old stars in it.

In brief, the life story of stars is that they are born in giant molecular clouds composed of gas and dust that are major concentrations of the interstellar matter. When a forming star contracts under the force of gravity, if the gravitational force were unchecked, it would squeeze the star down to nothing. Opposing forces, principally gas pressure, counterbalance this contraction. However, the gas pressure holding up the weight of the overlying layers would be decreased by the loss of energy as a star radiates, if the star did not replace the energy through hydrogen burning and other thermonuclear fusion processes. (By hydrogen burning we mean those nuclear reactions in which low-mass nuclei, like hydrogen, are fused together at very high temperatures to produce heavy nuclei plus energy; we do not mean ordinary combustion, which involves atomic and molecular reactions.) During a star’s life, the "ashes" of one nuclear-burning phase provide the fuel for the next burning phase. Eventually, stars exhaust all available nuclear fuels and end their lives as
primarily white dwarfs, but the rarer large mass stars appear to meet their end as either a neutron star or black hole.

In its simplest form, this is the life story of the vast majority of stars. The details of this story are best understood by using the Hertzsprung-Russell diagram as the central focus around which to weave the many varied aspects of a star’s life. The H-R diagram is our most important tool for studying stars in that it allows us to organize stellar data and to look for relationships among various types of stars. But first let us consider the basic physical principles of how stars are put together. And there is no more important idea than why gravity does not compress stars down to mere points.

17.1.2 Hydrostatic Equilibrium and Ideal Gases

For a star to resist the compression of gravity, or for that matter to neither expand nor contract, the upward forces on each layer from its center to its surface must equal the downward force. Such a condition is called hydrostatic equilibrium, and is described by the statement that:

\[
\text{Hydrostatic Equilibrium: At any distance from the center of a star, if the weight of overlying layers is balanced by the upward pressure of hot gas in layers closer to the center, then the star is said to be in a state of hydrostatic equilibrium.}
\]

Through most of a star’s existence, the gases inside the star conform to what is called the perfect-gas law, which says that:

\[
\text{Perfect Gas Law: In an ideal or perfect gas, the particles composing the gas occupy only a negligible portion of the volume, and when the gas particles collide, they do so quickly bouncing off each other like tiny billiard balls. For a perfect gas, the pressure of the gases (which results from the forces imparted by collisions) is directly proportional to the density and temperature of the gases.}
\]

At the high temperatures inside stars collisions between gas particles will strip electrons from atoms, leaving a plasma of bare nuclei and free electrons. Because most of an atom is just empty space, free electrons and bare nuclei can crowd much closer together in a plasma than they can in a gas composed of atoms, allowing the material inside stars to remain gaseous even at very high density. In the high-temperature and high-density regions near a star’s center, gas particles increase their speed and so collide more often and more violently. Consequently, the pressure exerted by the gas is greater in the center and declines outward. If the gas pressure exceeds the force of gravity, a star must expand; if gravity is greater, a star should contract. Thus each layer inside a star will undergo adjustments if a net force exists until hydrostatic equilibrium is restored.

For the hottest stars on the main sequence, the high-energy photons of very intense radiation fields inside these stars can add an additional pressure, a phenomenon known as radiation pressure, which along with the gas pressure helps balance the weight of overlying layers.

17.1.3 Thermal Equilibrium
During most of a star’s existence, it maintains itself in a state that we call thermal equilibrium. By this we mean that:

Thermal Equilibrium: In thermal equilibrium, the amount of energy generated inside a star equals the amount radiated away into space as luminosity at its surface. As a result, the temperature and pressure at all points inside such a star remain reasonable constant during such a period.

Thermal equilibrium is self-regulating in that if more energy is released in a star’s center than is radiated away at its surface, the temperature inside the star rises. Because gas pressure depends directly on temperature, the pressure increases, and such a star should expand, with heat or thermal energy being transformed into gravitational potential energy. This change in turn cools the gas, decreasing the gas pressure, and hydrostatic equilibrium is achieved at a larger radius. If, however, too little energy is produced, a star will contract and heat up, which increases the gas pressure and stops further contraction. Hydrostatic equilibrium is now found at a smaller radius.

What would happen if gas pressure did not depend on temperature? Heating or cooling from changes in the amount of energy generated would not be checked by increasing or decreasing the gas pressure followed by subsequent changes in a star’s size. Such a situation does happen and is called a degenerate gas. It may apply to all constituents of a gas or to only one of them, such as to free electrons, in which case it would then be called a degenerate electron gas. In Section 18.2, we shall see the significance of the development of degeneracy in stars.

17.1.4 Degenerate Gases

17.1.5 Transporting Energy

Energy may be transported in one or more of three distinct ways, although usually one means is more efficient than the others under the prevailing conditions. One of these means is conduction, which is the way heat is transferred along a metal rod placed in a fire. In the interior of main-sequence stars obeying the perfect-gas law, this is a very ineffective means of energy transfer. In the cores of stars where the material has become degenerate, however, conduction becomes the primary means of transporting energy.

A more frequently occurring means for transporting energy in stars is convection, in which gas circulated between hot and cool regions, transferring thermal energy to the cool region (Figure 17.1 and Section 16.1). Once a pattern of circulation is established, convection can be a very efficient mechanism of energy transport. For layers in which temperature changes quite rapidly with depth, convection develops as the principal means of carrying energy. These layers are referred to as a convective zone, and in them the atomic constituents are well mixed by the continual stirring.
Radiation is the third way of moving energy. Inside a star, photons resulting from energy-generation processes diffuse outward through overlying material. After a photon is emitted, it very soon is either absorbed by an atom (or ion) or scattered by free electrons after traveling a characteristic distance that ranges from very small fractions of a centimeter deep in a star’s interior to several kilometers in its photosphere. Although the direction in which a reemitted or scattered photon can move is generally arbitrary, there will be a net drift of photons outward from the center to the surface. Where energy is transported by radiation, such layers are known as a radiative zone. In a radiative zone, chemical elements go through very little mixing; any chemical inhomogeneity developing here should persist.

17.1.6 Opacity

Radiation and matter continually interact by absorption, reemission, and scattering of photons, processes that impede the outward flow of radiant energy (Figure 17.1). Such processes constitute what is known as the matter’s opacity.

Opacity: Matter’s resistance to the flow of radiation through it is measured by its opacity. If the resistance is almost complete, then we say that the matter is opaque to radiation of that particular wavelength or interval in wavelength. If the resistance is minimal, then we say that the matter is transparent to radiation of that particular wavelength. For example, concrete block walls are opaque to visible light but transparent to radio-wavelength radiation.

For stars, in regions of large opacity, the temperature drops rapidly outward, and convection will take over as the primary way of transporting energy. When the density is low, radiation travels more freely through a star.

Energy is liberated in the deep interior of stars as a comparatively small number of high-energy gamma-ray photons. As these photons work their way outward, absorption and reemission by overlying matter degrades the gamma-ray photons into millions of lower-energy ones by the time they reach the photosphere. Radiant energy takes hundreds of thousands of years to diffuse through the Sun from its energy-generating core.

17.2. Energy Generation

17.2.1 Thermonuclear Fusion

Over a century ago astronomers understood that the energy already radiated by the Sun could never have been supplied by ordinary combustion (for example, by the burning of wood or coal). Another way of producing energy known to astronomers was by the conversion of gravitational potential energy into heat during contraction. In fact, in the nineteenth century, this was thought to be the only source for the Sun’s energy. We now know that contraction is a vital source of energy on which a star can draw at various stages in its life. But at its current luminosity, our Sun could not have survived on gravitational potential energy alone for more than about 15 million years.
For stars like the Sun, a source of energy must keep the luminosity approximately constant for billions (not just millions) of years. The question plaguing astronomers in the early part of this century was what that source is. The answer is the fusion of small-mass nuclei to form more massive nuclei. Sir Arthur Eddington (1882-1944) suggested in 1920 that fusion of hydrogen could form helium and that this could be the long-sought fuel. After it was found that stars have vast quantities of hydrogen, the physicist Hans Bethe (b. 1906) proposed in 1938 a way in which four hydrogen nuclei (four protons) could be converted into a helium nucleus, releasing energy. If many hydrogen nuclei are converted, they will release sufficient energy through this process (known as thermonuclear fusion) to keep stars shining for billions of years.

What determines whether hydrogen can be fused to form helium? The answer is the temperature and density of a gas: the higher the temperature and density, the more readily the process will proceed. Thermonuclear reactions will therefore be most numerous in a star’s central region, where the temperature and density are highest. The reactions will gradually decline to zero somewhere out from the center, where temperature and density are too low to sustain them. This distance from the center, then, defines the energy-generating core of a star.

[Biography - Arthur Stanley Eddington (1882-1944)]

17.2.2 The p-p Chain and CNO Cycle

Hydrogen burning proceeds by two principal schemes (Figure 17.2): the proton-proton chain (p-p chain) and the carbon-nitrogen-oxygen cycle (CNO cycle). In each process, four protons are fused into one helium nucleus with a slight loss in mass, which is converted into energy. Which thermonuclear process produces more energy depends on the temperature. Up to about 16 million K the p-p chain dominates. Beyond that temperature, however, the CNO cycle takes over as the most important thermonuclear process. The average rate of energy generation for the entire Sun, which depends primarily on the p-p chain, is about 2 erg/g.s. For a star of 10M., the average rate of energy generation, supplied principally by the CNO cycle, is about 1000 times greater than that of the Sun.

[Figure 17.2]

The mass of the end product of hydrogen burning, He4, is 0.71 percent less than the combined masses of four reacting protons (H41). What has happened to the rest of the mass? Early in this century Einstein pointed out that there is an equivalence between mass and energy. Mass is just one more manifestation of energy, and what is conserved in any type of interaction between particles of matter is the total energy, including the energy equivalent of the mass. The equivalence is symbolized in Einstein’s equation \( E = mc^2 \), where \( E \) is the energy, \( m \) is the mass, and \( c \) is the velocity of light.

In hydrogen burning 1 g of hydrogen is converted into 0.9929 g of helium plus \( 6.4 \times 10^{18} \) erg of energy—exactly 0.71 percent of the original 1 g of hydrogen times \( c^2 \). In what form does the energy appear? In the various steps, several gamma-ray photons are created and
translated into practical units, every second the Sun converts 600 million metric tons of hydrogen into 596 million metric tons of helium and 4 million metric tons of mass into energy. This energy will diffuse to the surface, where it will supply the $3.83 \times 10^{33}$ erg of energy radiated away into space each second. In its core the Sun has enough hydrogen to keep it shining for about 10 billion years. In 4.6 billion years the Sun has existed so far, it has used up about half its core's hydrogen supply and lost about 0.043 percent of its mass.

17.2.3 Steps in Hydrogen Burning

Step 1 in the p-p chain (Table 17.2) is fusion of two colliding protons ($H_1$) to form a deuteron ($H_2$), which is the nucleus of the hydrogen isotope deuterium, resulting in the emission of a positron ($e^+$) and a neutrino ($\nu$). This reaction happens, on average, once every 14 billion years for each isolated pair of protons. The time for the entire thermonuclear process is determined by this first step, and it is only the enormous quantity of hydrogen in the cores of stars that makes this process a significant source of energy.

The positron is a positively charged particle with the mass and other characteristics of an electron; it is the antiparticle for the electron. The collision of a positron with an electron destroys them as matter and creates two gamma-ray photons. The neutrino, however, is a massless, chargeless particle that moves at the speed of light. Since the neutrino has a low probability of interacting with matter, it immediately escapes from the star, carrying away about 2 percent of the energy released in the p-p chain of reactions.

Step 2 in the p-p chain is the collision within a few seconds of another proton with the deuteron to fuse and form the light isotope of helium ($He_3$), resulting in the emission of a gamma-ray photon. Finally, in step 3, two $He_3$ nuclei collide every few million years and fuse to form the heavy isotope of helium ($He_4$), accompanied by the return of two protons. (We should point out that there are other branches of these reactions leading to the same end.)

All told, six protons have taken part in producing two $He_3$ nuclei, from which one $He_4$ nucleus is produced and two protons are returned to the reservoir of fusionable matter.

The other hydrogen-burning reaction, the CNO cycle, has six steps occurring at rates between 80 seconds and 300 million years but leading to the same result as the p-p chain: that is, the conversion of four protons to produce one helium nucleus and to liberate energy. The cycle begins with $C_{12}$ and closes with the return of $C_{12}$, so that carbon is thus only a catalyst that makes the reaction go.

17.3 Mathematical Models of Stars

17.3.1 Constructing Stellar Models
Each of the physical processes described in the preceding section depends on several physical quantities, among them temperature, density, pressure, and the mass and luminosity of a star. We can use a symbol to represent the numerical value of each quantity and combine these symbols into mathematical equations embodying their relationships. These equations, called equations of stellar structure, describe how mass, pressure, temperature, and luminosity vary outward from the center of a star. Within these equations are additional quantities, such as density, chemical composition, opacity, and the rate at which energy is generated. To construct models of stars, we take their observed properties—such as mass, radius, luminosity, surface temperature, and estimated chemical composition—as constraints in solving the equations of stellar structure at a discrete number of points along the radius. The solution is a mathematical model, or a stellar model. The computer makes it possible to calculate these models in reasonable lengths of time for several hundred points. Without the high-speed digital computer, much of the progress we have made in the last 20 years in this field would not have been possible.

An example of such a mathematical model for the Sun at present is given in Table 17.3 and is shown schematically in Figure 17.3. As a star evolves, it alters the structure of its layers from center to surface. The chemical composition is also changing in the layers responsible for nuclear burning.

Table 17.3

Figure 17.3

We can calculate a sequence of mathematical models simulating the restructuring that real stars presumably undergo as they age during their life spans of millions of human generations. For each model in a sequence, the surface temperature and luminosity are a point in the H-R diagram for a particular stellar age. How do we test the validity of our models? We see how well this time sequence of points, or evolutionary track, for one star helps us predict the distribution of real stars in the H-R diagram. Both open and globular clusters are important observational keys in checking our results. The color-magnitude diagrams of clusters, such as Figures 14.16 and 14.17, give the best evidence on stellar aging because a cluster is a group of stars with a definite range of masses that began their existence at about the same time and in the same place. They also formed from the same material and so at first were reasonably similar chemically. From the distribution of cluster stars in the H-R diagram, we can then deduce details of how individual stars age.

17.3.2 Oscillations of the Sun

The Sun radiates as much energy away from its surface as is liberated in its interior. If it did not, the photosphere would cool down or heat up, which does not appear to be happening. The Sun is in a state of thermal equilibrium, with the temperature declining from some 15 million K at the center to about 6000 K in the photosphere. The density also declines from a central value of about 160 g/cm³ to a mere 10⁻⁷ g/cm³ in the photosphere. The drop-off in density is so rapid that most of the Sun’s mass is in its deep interior, close to the center; in fact, some 90 percent of its mass lies within 50 percent of the radius.
Sparked by the discovery of 5-minute solar oscillations in the early 1960s a number of astronomers were able to show that the Sun is also vibrating with periods of tens of minutes up to 160 minutes. Thus the Sun vibrates much as a ringing bell does (Figure 17.4). Just as oscillations of the Earth in the form of seismic waves after earthquakes can be used to probe the Earth’s interior, these solar oscillations are indicative of the physical conditions inside our Sun. As such, they can be used to verify the theoretical interior structure that we described earlier. This relatively new field of solar research is called solar seismology, and such efforts as setting up telescopes at the South Pole to observe solar oscillations around the clock will eventually provided a first-hand understanding of the solar interior.

[Figure 17.4]

17.3.3 Solar Neutrino Experiment

How certain are astronomers about the thermonuclear processes going on inside stars? So far, the only experiment designed to test the theory directly is one that tries to detect the neutrinos created in thermonuclear processes. Neutrinos pass freely out of the Sun into space, and so carried away with them, at the speed of light, is a small fraction of the energy generated in the Sun. By detecting solar neutrinos, we can have first-hand information on the average temperature in the hydrogen-burning core.

One scheme for detecting solar neutrinos uses a huge tank filled with 400,000 liters of dry-cleaning fluid (Figure 17.5). It is located deep in a South Dakota gold mine to shield the chlorine atoms in the solvent from cosmic-ray particles; nothing is allowed to reach them but neutrinos. When the nucleus of a chlorine atom (Cl37) captures a neutrino, which is not often, it is transformed into radioactive argon (Ar37), which has a half-life of about 35 days. The argon nucleus is recovered, and its decay is monitored. We find that the observed flux of solar neutrinos is about four times smaller than the rate predicted from standard mathematical models of the Sun. By manipulating the solar model, which is subject to some uncertainties anyway, the discrepancy can be reduced but not eliminated. Other explanations for the discrepancy have been proposed, but none has received widespread endorsement. Plans are being made for a new experiments that will measure the lower-energy neutrinos that are not counted in the experiment just described.

[Figure 17.5]

Recently, another explanation has arisen as a result of two studies of the historical measurements of the Sun’s diameter. Both studies seem to find that the Sun has been shrinking for the last 100 or so years. The question is by how much. The contraction, if real, amounts to about 0.01 to 0.1 percent per century. Further speculation prompted by this finding suggests that the Sun may undergo a long-term cycle of very slow expansion and contraction. During contraction, the Sun derives heat energy from gravitational potential energy and lowers its rate of hydrogen burning. This would account for the emission of fewer neutrinos. These results are a long way from being thoroughly verified.
The solar neutrino problem is serious, for it casts doubt on our knowledge of the details of structure and/or energy generation in main-sequence stars. Thus we are forced to look more carefully at the details of these processes in the Sun if the experiment is completely correct. But it is unlikely that the solar neutrino problem forecasts the failure of the present theory of stellar evolution. The details of the theory will change over time as a result of the solar neutrino problem and others, but the general outline, which is covered in the remainder of this chapter and the next two, seems likely to endure.

17.4. Main-Sequence Stars

17.4.1 Results from Studies of Stellar Evolution

If our knowledge of the physical processes going on inside stars is correct, we should be able to predict a star’s position in the H-R diagram at different stages of life. We can thus explain the existence of various regions of the diagram and trace the evolutionary sequence that carries stars from one region to another. One check is the observation that the fraction of stars in any region of the H-R diagram should equal the fraction of a star’s existence spent in that region of the diagram. For example, if the red supergiant phase is predicted to be a short part of a star’s life, we should see relatively few red supergiants--and we do. However, if the main sequence is predicted to be a long phase, then many stars should be main-sequence stars. The main sequence, as Table 20.1 shows, is actually observed to be the most densely populated region in the H-R diagram, as stellar evolution theory predicts.

Let us begin the study of the evolution of stars with the most common, the main-sequence stars. On this sequence, the hot stars of spectral classes O and B are the most massive ones, and the cool, red dwarfs of class M are the least massive.

17.4.2 Meaning of the Main Sequence

Stars spend most of their lives on or near the main sequence for two reasons: the large yield of energy per gram from hydrogen burning as compared with other sources of nuclear energy and the vast quantity of hydrogen available. The H-R diagram for the stars in the Sun’s immediate neighborhood (Figure 13.10) and the color-magnitude diagrams for open clusters (Figure 14.16) are illustrations of this fact.

The approximate time a star spends on the main sequence is proportional to its mass divided by its luminosity, which can be derived with the help of Einstein’s mass-energy equivalence. The more massive a star, the greater is its emission of radiant energy per gram of matter and the shorter its time on the main sequence. This point is illustrated by the numerical estimates in Table 17.4 for luminosity per gram and duration on the main sequence, given that the Sun will be a main-sequence star for about 10 billion years.

[Table 17.4]

Now let us consider the reason for the shorter hydrogen-burning phase for more massive stars. After a massive star contracts onto the main sequence, its central temperature must
be higher than that for lower-mass stars because it needs a higher gas pressure at its center to balance gravity. Consequently, the temperature difference between the center of a star and its photosphere will be larger the more massive the star is. For a 15M. star, the central temperature is around 35 million K compared with 7 million K for a star of 0.25M. More thermal energy flows from the interior of massive stars, making them more luminous than less massive stars. Also, the more massive a star, the more rapidly it must burn hydrogen to supply the energy loss from its surface. The CNO cycle in massive stars also depends more strongly on temperature and consumes hydrogen faster than does the p-p chain that operates in low-mass stars. The dividing line between the two is about 2M..

17.4.3 Mathematics of Main-Sequence Lifetimes

...

17.4.4 Main-Sequence Stars of the Night Sky

How does the time a star spends on the main sequence affect the stars in our night skies? A star such as Spica, in the constellation Virgo, is a B1 star, and although it may be just above the main sequence it is at most 15 to 20 million years old (Table 17.5). Stars such as Sirius in Canis Major and Vega in Lyra are early A stars and are less than 500 million years old (Figure 17.6). The main-sequence life of nearby Barnard’s star, an M5 red dwarf in the constellation Ophiuchus, is greater than 200 billion years, and it will still be fusing hydrogen in its core long after the Sun has ceased to shine. During the Sun’s 4.6 billion years on the main sequence, thousands of massive O and B stars have come into existence and long ago left the main sequence, but all the small-mass M stars born in that period have hardly begun their stay on the main sequence.

[Figure 17.6]

17.4.5 Limits of the Main Sequence

How much matter is necessary to form a star? How large a mass may a star have? If we say that a star is an object that is or has been self-luminous and is held together by gravity, then the smallest mass for a star that derives energy from thermonuclear burning is about 0.1M. This limit is set by the mass needed to produce a central temperature sufficient to initiate hydrogen burning. Yet objects as small as 0.01M. can survive a very long time on just the energy from gravitational contraction. Such "stars" are called brown or infrared dwarfs, but they are expected to be so faint that only a few objects are seriously considered as candidates. These possible brown dwarf candidates (Table 17.5 and Figure 17.7) are companions to low-mass M dwarfs that are very nearby and have been discovered by astrometric binary techniques. Because the masses of the brown dwarfs apparently are a few tens of times that of Jupiter, astronomers suspect that the physical processes in their interiors are the same as in Jupiter’s interior. Studies to date support that suspicion.

[Table 17.5]

[Figure 17.7]
At the upper end of the main sequence the mass of a star is probably determined more by the amount of interstellar matter available when it was formed than by its internal structure. Stars of about 60M. and greater have such a delicate balance between gravitational and pressure forces that equilibrium could be prevented by any irregularities of motion inside the star. There are a few O stars for which mass estimates suggest that they are near 100M. Limits on the masses of main-sequence stars determined from binaries are consistent with these figures.

In the next section we shall examine the birth of stars or the process that brings them to the main sequence, while in Chapter 15 we will explore the aging processes that carry stars away from the main sequence toward their deaths.

17.5. Birth of Stars

How and where are stars born? Observational evidence points to the interstellar gas and dust clouds along the Galaxy’s spiral arms (Figure 14.1) as being the birthplaces of stars. As some stars--such as those responsible for planetary nebulae, novae, and supernovae--approach the end of their lives, they return some of their mass to the interstellar medium. New generations of stars are thus forming from the ”ashes” of previous generations.

17.5.1 Collapse of Interstellar Clouds

Apparently the particles composing interstellar matter are not subjected to a net force by which an excess gravitational attraction from their neighbors pulls them together. If they were, within several hundred million years all the matter in the interstellar medium would collapse and fragment into stars. Thus all the interstellar matter would have been used up early in the Galaxy’s history, and no more stars could form.

The very existence of interstellar matter and its organization into clouds of up to several hundred thousand solar masses argues that the gas pressure in clouds is sufficient to balance the effects of gravity. The first step in making new stars is to compress a cloud to strengthen gravity’s effect so that the cloud material can contract and fragment into smaller units that eventually collapse to form stars.

A promising way of getting this process going is the traveling compression wave, or density wave, which astronomers believe is responsible for the Galaxy’s spiral arm structure (Figure 20.14). As the wave moves past a cool molecular cloud, it compresses the cloud, driving the particles closer together. Their mutual gravitational attraction is now greater than the gas pressure. If the compressed cloud has no other force that can halt contraction, collapse continues until the matter heats up, raising the gas pressure sufficiently to resist further contraction.

Another possible mechanism for compressing molecular clouds is supernovae outbursts. An expanding shock front on the leading edge of the gas shell expelled by a supernova outburst impinges on nearby clouds and compresses them by factors of 10 or more, triggering gravitational collapse. The discovery that some young stellar associations are
located inside the expanding shells of old supernova remnants certainly makes this a believable mechanism.

Finally, the collapse of clouds could begin if a cloud could be cooled so that the gas pressure would go down. There are several possible ways of cooling clouds, such as dust grains radiating away energy as infrared radiation.

Regardless of what starts the process, a fragmenting molecular cloud breaks into smaller units, and the fragments attract more matter and grow in mass. The rate at which stars are created from fragments of an interstellar cloud and the number of stars of different masses formed probably depend on several factors: total mass, density, temperature, magnetic fields, and the amount of internal motion stirring the material. The mechanism forming stars favors clearly small-mass stars, since we observe many more small-mass stars than large-mass ones. Finally, it appears that only a small fraction, 1 or 2 percent, of the matter in dark clouds actually forms stars.

17.5.2 Bok Globules

Small, dark blobs have been photographed against many of the bright star-filled regions and luminous H II nebulosities of the Milky Way. They are called Bok globules (Figures 17.8 and 17.9) in honor of astronomer Bart Bok (1906-1983). Globules are typically a few light years in size (hundreds to thousands of times the size of the Solar System), they possess densities of cold molecular hydrogen and dust of several tens of thousands of particles per cubic centimeter, and they contain several tens of solar masses of material. A number are known in which young stars of up to a few solar masses are embedded. This suggests that they are indeed part of the star formation process. The famous Horsehead Nebula shown in Figure 17.10 is probably a Bok globule in formation.

[Figure 17.8]

[Figure 17.9]

[Figure 17.10]

Matter in collapsing fragments converts its gravitational potential energy into thermal energy, some of which is radiated away into space as infrared radiation. At some point, however, a significant amount of energy goes into dissociating molecular hydrogen to form atomic hydrogen; later more energy is needed to ionize all chemical species. Because this energy used to dissociate and ionize is not available as thermal energy, the collapsing fragment is prevented from achieving hydrostatic equilibrium. Consequently, in a very short time (hundreds to tens of thousands of years), the fragment collapses from a small fraction of a light year in diameter (several million solar radii) to a few thousand solar radii (Figure 11.3).

During collapse of a fragment, its matter has been growing hotter and emitting more visible light and less infrared radiation. Because it is cooler, however, dust in the surrounding stellar nebula out of which the star is forming absorbs visible photons, heats
up, and reemits the energy in the infrared. Thus the stellar nebula conceals the developing star until most of the surrounding gas and dust is either attracted to it or blown out of the system by it.

There are several examples in which astronomers have apparently witnessed interstellar dust rearranging itself over a period of years to reveal, if not a developing star, the place where one or more stars will be eventually.

17.5.3 Protostars, First Appearance on the H-R Diagram

Eventually, the central regions of a forming star become opaque and slow the outward flow of radiation. The effect of this is to stem the loss of energy so that the temperature rises and the gas pressure increases. This causes the central region to slow from a free-fall collapse to a gradual contraction as it approaches a balance between gas pressure, which is pushing outward, and weight resulting from gravity, which is pushing inward. Now the embryo star can appear on the H-R diagram for the first time; it begins its evolution on the coolest fringes of the diagram on evolutionary tracks determined from stellar models (see the right-hand side of Figure 17.11).

[Figure 17.11]

Once the forming star has stabilized somewhat, it is in the red-giant region of the H-R diagram, although it is not called a red giant; it is a protostar. The temperature of a protostar's surface is about 4000 K, and energy in its deep interior is transported to the surface entirely by convection, which extends from center to surface. In this slower-contraction phase, a protostar decreases its luminosity but keeps about the same surface temperature; most of the accretion of matter has stopped.

Gravitational contraction eventually raises the temperature in a protostar's core to 1 million K or so, which is hot enough to destroy by nuclear reactions such light nuclei as deuterium, lithium, beryllium, and boron (initially present in small quantities). These are the first stages of the star's thermonuclear existence, from which it derives very little energy; the next stage is to initiate hydrogen burning.

By the time a protostar's central temperature has risen to several million degrees, the p-p chain can be ignited and hydrogen burning begins to supply some luminosity, at first in small amounts. Several million years later the protostar arrives on the zero-age main sequence in the H-R diagram, where hydrogen burning supplies 100 percent of the luminosity and contraction has virtually ceased. Astronomers define the zero-age main sequence (Figure 17.11) as the line along which protostars of different masses cease to contract (and thus are stable configurations) and derive all their luminosity by burning hydrogen. The protostar is now a full-fledged star.

How long does it take to go through the protostar stage to reach hydrogen burning? For the Sun it was about 30 million years; approximate times are listed for other stellar masses in Figure 17.11. As the figure shows, stars exceeding the Sun's mass evolve quite rapidly, while for less massive stars the protostar phase is longer than that for the Sun. It is usual
among astronomers to date a star’s age from the zero-age main sequence onward, since the time it has spent contracting out of the interstellar medium to the main sequence is only a small fraction of its life span, typically a few tenths of a percent.

Some stellar models indicate that protostars with masses of less than about 0.1M$_\odot$ never become hot enough at their centers to fuse hydrogen. They pass the lower end of the main sequence and continue contracting toward extremely high densities. These very low mass "stars" apparently bypass normal stellar evolution and proceed slowly to becoming brown dwarfs. With less than a 0.01M$_\odot$ such protostars may become Jovian-type planets (Jupiter’s mass is 0.001M$_\odot$).

There is little doubt among astronomers that rotation is also a crucial factor during the collapse of interstellar clouds and the contraction of the resulting fragments through the protostar stage into main-sequence stars. Rotation probably determines whether the results will be multiple-star systems (high rotation), binaries, stars with brown dwarf or planetary companions, or just single stars (low rotation).

17.5.4 Stellar Nurseries

By the time several O stars arrive on the zero-age main sequence from the collapse of a giant molecular cloud, they will produce enough ultraviolet radiation to evaporate dust grains and ionize gas in their vicinity; this process forms an H II region. Figure 17.12 is an attempt to depict the formation of an O association on one end of a giant molecular cloud. Star formation advances across the cloud by the formation of new O stars. This occurs because the O stars’ emission of ultraviolet radiation (which forms the H II region) in conjunction with their stellar wind creates a shock front that compresses the cloud. This in turn initiates new fragmentation and collapse, forming more stars. When the massive O stars reach the end of their lives, they also undergo a supernova outburst that adds to the compression of the cloud and furthers star formation. Finding H II regions in dark-cloud complexes definitely demonstrates that stars are forming, as the example in Figure 17.13 shows.

We do not definitely know whether all stars that will originate in a giant molecular cloud form simultaneously. The formation of individual stars may spread over a period as long as 10 million years. However, when a molecular cloud begins to fragment in selected regions into a cluster of protostars of differing masses, the evolving stars will reach the main sequence at different times according to their mass. The more massive stars begin burning hydrogen first, and in beadlike progression the others arrive along the zero-age main sequence from upper left down to the lower right in the diagram. Stars of lower mass will lie progressively farther above and to the right of the zero-age main sequence at any instant in time after contraction starts.

The open cluster NGC 2264 shows this progression quite well in the H-R diagram in Figure
The less-massive cluster stars should eventually arrive on the lower portions of the main sequence in order of their mass. Many of the cluster's stars even have gas and dust shells. The cocoons, or shells, around these stars contain large quantities of dust apparently inherited from the original giant molecular cloud. The dust absorbs visible light from the forming star, heats up to several hundred K, and reradiates the energy as infrared radiation. Thus infrared studies can reveal what goes on in "stellar nurseries."

Additional evidence that can be used to identify recently formed stars comes from the coexistence of T Tauri variable stars in open clusters and veiling clouds, out of which they seem to have originated. The T Tauri variables have characteristics that we might expect for objects going through pre-main-sequence evolution; in particular, they lie above the main sequence in the H-R diagram. Sometimes very massive O and B stars, which are definitely quite young and already on the main sequence, are intermingled with T Tauri stars. It is presumed that T Tauri stars are in the 0.2 to 3.0M range, contracting toward the main sequence. Typical radii measured for them are about five times that of the Sun.

About 4.6 billion years ago, after being a protostar some 30 million years, the Sun settled on the main sequence for a long, uninterrupted period of hydrogen burning. This stable phase in its life should continue for another 5 billion years. A star's time on the main sequence is the longest and most quiescent phase in its life. As hydrogen burning progresses, the energy-generating core is depleting hydrogen and converting it to helium. Because gas pressure depends on density, or number of particles, converting four hydrogen nuclei to one helium nucleus must reduce the gas pressure. Hydrogen burning will therefore be accompanied by a slight contraction of the energy-generating core and a heating up of the material. Because this increases the temperature difference between the center and surface causing a greater outflow of radiation, a star brightens slightly; the outer portion of the star also expands, increasing the radius. This is part of the reason for some of the width of the main sequence evident in H-R diagrams. As noted earlier, estimates from mathematical models for the Sun suggest that it has increased its luminosity by 20 to 30 percent during its 4.6 billion year existence as a main-sequence star. After the Sun exhausts its hydrogen fuel, it must undergo some relatively rapid changes that lead eventually to its death, as we shall see in the next chapter.