Part I Star Formation in Our Galaxy

The complex of processes known as star formation must have occurred innumerable times in the remote past. The Big Bang, after all, did not produce a Universe full of stars but of diffuse gas. How gas turns into stars is the subject of this book. Anyone wishing to study the problem is aided immeasurably by the fact that star formation is also occurring now, and in regions close enough that the transformation can be examined in some detail. Indeed, most research activity in this field consists of our bold, if frequently misguided, attempts to interpret what is in fact happening all around us.

We begin, therefore, with the data. The four chapters of Part I describe various aspects of star formation activity in our own Galaxy. We discuss the properties of the gas in interstellar space, the structure of clouds that produce stars, and the morphology of young stellar groups. The treatment here is quite broad, since all these topics will be revisited later. Our very first task is to introduce the reader to the primary objects of interest, young stars themselves, and to the environments in which they are born. We start with a descriptive tour of two relatively nearby regions, before proceeding to a more quantitative and physical description of stars and their evolution.

1.1 Stellar Nurseries: Orion

The figure of Orion the Hunter is a familiar sight in the winter sky of the Northern hemisphere. It is one of the most easily recognized constellations and includes one tenth of the 70 brightest stars. Less familiar, perhaps, is the fact that this area is an extraordinarily active site of stellar formation. Over the years, no similar region has received such intense astronomical scrutiny, nor been studied with such a variety of observational tools. We refer the reader to the sky map of Figure 1.1. Here, some of the more conspicuous of the constellation's members are indicated, including the red supergiant Betelgeuse at the Hunter's right shoulder, and brilliant blue Rigel at his left foot. South of the three stars that comprise the belt of the Hunter is a bright, fuzzy patch. This is the Orion Nebula, a cloud of gas being heated by the intense radiation of the Trapezium stars embedded within it.

1.1.1 Giant Molecular Cloud

Young stars like those of the Trapezium are forming out of a huge body of gas known as the Orion Molecular Cloud. The extent of this object is indicated by the shading in Figure 1.1. In its longest dimension, the cloud covers 15° in the sky, or 120 pc at the distance of 450 pc.¹ Orion is but one of thousands of *giant molecular clouds*, or *cloud complexes*, found throughout the Milky Way. The gas here is predominantly molecular hydrogen, H₂. With their total masses of

¹ The reader unfamiliar with units commonly employed in astronomy, such as the parsec (pc), should consult Appendix A.

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Figure 1.1 A portion of the Northern sky. The Milky Way is depicted as light grey, while the darker patches indicate giant molecular clouds. Also shown, according to their relative brightness, are the more prominent stars, along with principle constellations.

order $10^5 M_{\odot}$, these structures are the largest cohesive entities in the Galaxy and are almost all producing new stars.

The fact that we know of molecular clouds at all is a triumph of radio astronomy. Gas in these regions is much too cold to radiate at visible wavelengths, but may be detected through its radio emission in trace molecules such as CO. Here observers most often rely on single dishes that can map extended areas of the sky. For more detailed studies of individual regions, one may utilize the fact that several dishes linked together effectively increase the detector area and hence the angular resolution. Such *interferometers* have been powerful research tools, especially for studying the distribution of matter around newly formed stars.

The left panel of Figure 1.2 is a high-resolution CO map of the entire Orion molecular cloud. In this case, the observations were made with a relatively large single-dish telescope. The spectral line being detected is the commonly used 2.6 mm transition of the main isotope, ${}^{12}C^{16}O$. We have distinguished in the figure two major subunits, labeled Orion A and B. Both the elongated shape of the whole complex and its high degree of clumpiness are generic features of such structures.

Along with their gas, molecular clouds contain an admixture of small solid particles, the *interstellar dust grains*. These particles efficiently absorb light with wavelengths smaller than their diameters (about $0.1 \,\mu$ m) and reradiate this energy into the infrared. Regions where the dust effectively blocks the light from background stars are traditionally known as *dark clouds*. Generally, these represent higher-density subunits within a flocculent cloud complex, although they can also be found in isolation. Note that the extinction due to dust depends on its *column density*, *i. e.*, the volume density integrated along the line of sight. Figure 1.3 depicts the major dark clouds in Orion, determined by tracing the regions of strong obscuration in optical photographs. A number of the most prominent structures, such as L1630 and L1641, are labeled by their designations in the Lynds cloud catalogue. The shaded areas, including those with NGC numbers, are chiefly *reflection nebulae*, *i. e.*, dusty clouds that are scattering optical light from nearby stars into our direction.²

The mid- and far-infrared emission from warm dust particles provides yet another means to study the Orion region. The first instrument devoted exclusively to infrared mapping of the sky was IRAS (for *Infrared Astronomical Satellite*), launched in 1983. Figure 1.4, which spans the same angular scale as the previous two figures, shows the Orion Molecular Cloud as a composite of three monochromatic IRAS images taken at 12, 60, and 100 μ m. Radiation in this spectral regime comes mainly from dust heated to roughly 100 K. The fact that even this modest temperature is maintained over such an extended region demands the presence of many stars of high intrinsic luminosity.

Returning to the ¹²C¹⁶O map of Figure 1.2, we see that several areas associated with reflection nebulae have closed, nested contours, indicating a local buildup in radio intensity. The received intensity in ¹²C¹⁶O is correlated with the hydrogen column density, so that such buildups mark the presence of embedded clumps. The 2.6 mm transition is most readily excited by gas with number density near 10³ cm⁻³ and is relatively weak at higher values. However, other tracers are available to explore denser regions. The inset in Figure 1.2 is a map of Orion B in the 3.1 mm line of CS, a transition excited near 10⁴ cm⁻³. Here, most of the individual fragments have sizes of about 0.1 pc and inferred masses near 20 M_{\odot} , while the few largest ones have masses ten times as great. Such localized peaks within the broad sea of molecular cloud gas are known as *dense cores* and are the actual sites of star formation.

The stars being born within dense cores shine copiously in optical light, but none of this short-wavelength radiation can penetrate the high column densities in dust. As before, however, the same dust can be heated to emit at wavelengths that *can* escape. The shaded portions of the Figure 1.2 inset show regions detected at 2.2 μ m. What is being seen, in fact, are several

² The *NGC* designation is historical and refers to the "New General Catalogue" of nebulous objects, dating from the 19th century.



Figure 1.2 Map of the Orion Molecular Cloud in the 2.6 mm line of ${}^{12}C^{16}O$. See Appendix A for an explanation of the coordinates used here and elsewhere in the book. The insert shows a detail of Orion B in the 3.1 mm line of CS. Shading within the insert marks those regions which emit strongly at 2.2 µm. The (0,0) point coincides with the position of the reflection nebula NGC 2024. This nebula and others are indicated by crosses.



Figure 1.3 Dark clouds in Orion. The large swath is Barnard's loop, a diffuse region of enhanced optical emission. The labeled dark patches are reflection nebulae. Major clouds are also labeled by their Lynds catalogue numbers.

1.1 Stellar Nurseries: Orion



Figure 1.4 Infrared view of the Orion Molecular Cloud. This is a composite of three monochromatic images at 12, 60 and 100 µm.

embedded stellar *clusters*, compact groups containing tens to hundreds of members. Each cluster is associated with one of the more massive bodies of molecular gas, and virtually all cluster members are still nested within their parent dense cores. Thus, we see that stars form in giant molecular clouds at localized, massive peaks in the gas, and predominantly in a cluster mode, rather than in isolation.

1.1.2 Orion Nebula and BN-KL Region

To the south of Orion B, the Orion A cloud consists of a similar clumpy distribution of molecular gas. Within one elongated, high-density region is the famous Orion Nebula, also designated NGC 1976 or M42, the latter nomenclature referring to the 18th century Messier catalogue. As shown in the optical photograph of Figure 1.5 (*left panel*), the nebula is a turbulent expanse of gas, lit up by an embedded stellar cluster. The conspicuous ridge at the bottom of the photograph is the Orion Bar, whose emission also stems from gas heated and ionized by the cluster stars. This *ionization front* is seen edge on and is especially well defined because of the cool, dusty region just beyond it. The cluster responsible for such energetic activity is the Ori Id OB association, one of several small groups of massive stars in the giant complex. Near the center of the figure are the four stars of the Trapezium, whose most prominent member, the O star θ^1 Ori C, has a luminosity of $4 \times 10^5 L_{\odot}$ and a surface temperature of 4×10^4 K.

Stars this hot emit most of their energy in the ultraviolet and are thus capable of ionizing hydrogen gas out to considerable distances. The Orion Nebula, which is about 0.5 pc in diameter, is the best studied example of such an *HII region*. Within the ionized plasma, the gas temperature is comparable to that at the surface of the exciting star. As electrons and nuclei recombine, the atoms emit a plethora of spectral lines, including optically visible radiation from



Figure 1.5 *left panel*: Optical photograph of the Orion Nebula, with the Trapezium stars at the center. *right panel*: Infrared (2.2 µm) image of the same area. The BN-KL region lies at the upper right.



Figure 1.6 Expansion of the Orion Nebula (*schematic*). The insert depicts the blueshifted spectrum of the $n = 86 \rightarrow 85$ hydrogen recombination line, which has a rest-frame frequency of 10522.04 MHz.

both hydrogen and heavier elements. Here, these lines can be detected because the nebula sits near the edge of the Orion A cloud, as depicted in Figure 1.6. While the ionization created by the OB association slowly eats its way into the cloud, hot matter on the other side streams out into the more rarefied gas adjacent to the cloud. As sketched in the figure, this streaming motion in the direction of the Earth is evident from the Doppler shift toward the blue seen in hydrogen recombination lines. The ionized gas is approaching the Earth at a velocity of 3 km s⁻¹, while the Trapezium stars themselves are *retreating* at 11 km s⁻¹.

O and B stars, although intrinsically luminous, are produced only rarely within molecular clouds. Much more frequently, gas condenses into low-mass stars, *i. e.*, those of about $1 M_{\odot}$ or less. Thus, the Ori Id association is merely the tip of the iceberg in terms of stellar production, as sensitive optical and infrared surveys have now made clear. The O and B stars lie in the center of the populous Trapezium Cluster (also called the Orion Nebula Cluster). The right panel of Figure 1.5 shows over 500 stars in this region, as imaged at 2.2 µm. The photograph covers about $4' \times 4'$ in angular extent, or 0.6×0.6 pc. With its central number density in stars exceeding 10^4 pc⁻³, the Trapezium Cluster is among the most crowded star formation regions in the Galaxy.

The near-infrared image contains a bright region in the upper right that is invisible optically. This stellar cluster is actually located about 0.2 pc *behind* the Orion Nebula, in a portion of the cloud complex designated OMC-1 (see Figure 1.6). Here reside two mysterious and powerful sources of infrared radiation, the Becklin-Neugebauer (BN) Object and IRc2, each emitting



Figure 1.7 Mid-infrared (19 μ m) continuum radiation from the KL Nebula (*greyscale*). Prominent infrared objects are labeled. The contours show emission from the 1.3 cm line of NH₃.

luminosities from 10^3 to $10^5 L_{\odot}$. Both are part of the larger and more diffuse Kleinman-Low (KL) Nebula, which is about 0.1 pc in diameter. The greyscale image of Figure 1.7, representing emission at 19 µm, shows the area in more detail. To supplement this picture of the dust content, the superposed contours trace 1.3 cm radiation from heated NH₃ molecules. The NH₃ radio line is strongest where the dust emission is weak or absent. Since the molecule's emission is sensitive to the ambient temperature, this pattern suggests that the gas has been heated to the point where dust is thermally destroyed.

The BN-KL region is producing a massive *molecular outflow*, *i. e.*, high-velocity cloud gas streaming away from the infrared stars. The outflow phenomenon, ubiquitous in star formation regions, was first discovered here through detections of the Doppler shift in the ¹²C¹⁶O line. Observations of numerous other molecular species reveal that the impact of this wind on nearby gas has resulted in shock heating, which alters the pattern of chemical abundances in a characteristic manner. Also seen in the vicinity is copious near-infrared emission from H₂, resulting from collisional excitation of the molecule in shock fronts. Finally, the BN-KL region contains numerous *interstellar masers*, small regions of strongly beamed radiation from molecules such as H₂O and SiO. The measured intensity of these spots is vastly greater than that normally emitted at the ambient temperature of roughly 100 K. The maser phenomenon is yet another manifestation of wind-induced shocks in this extraordinarily active region.

1.2 Stellar Nurseries: Taurus-Auriga

Returning to Figure 1.1, we now proceed northwest from Orion, *i. e.*, along the direction of the Hunter's belt. We soon encounter the constellation Taurus (the Bull). Taurus is notable for the



Figure 1.8 Dark clouds in Taurus-Auriga. The large patches in the lower left and middle right correspond to TMC-1 and L1495 in Figure 1.9.

bright orange star Aldebaran, as well as for the Hyades, the V-shaped group of stars marking the Bull's face, and the Pleiades group riding his shoulder. Both the Hyades and Pleiades are nearby, young stellar clusters that continue to furnish valuable information for evolutionary studies. We are more interested, however, in an even younger region to the north, extending into the neighboring Auriga Constellation. Here, as in Orion, molecular clouds are actively producing a multitude of new stars.

1.2.1 Dark Clouds

The clouds of Taurus-Auriga, indicated as the shaded area of Figure 1.1, have long been noted even in optical images. Figure 1.8 is a photograph from early last century by E. E. Barnard, covering a region of about 50 square degrees. Here one sees prominent dark lanes in the otherwise rich stellar field. Referring to this photograph in his 1927 atlas of the Milky Way, Barnard wrote

Very few regions of the sky are so remarkable as the Taurus region. Indeed, the photograph is one of the most important of the collection, and bears the strongest proof of the existence of obscuring matter in interstellar space.

Even more convincing – indeed, definitive – proof of interstellar dust was to come several years later, with J. Trumpler's demonstration of the progressive reddening of distant clusters.

The molecular gas accompanying the obscuring dust can be seen most readily in ${}^{12}C^{16}O$, as shown in Figure 1.9. The Taurus-Auriga region covers a greater angular area than the Orion



Figure 1.9 Map of Taurus-Auriga in the 2.6 mm line of ${}^{12}C^{16}O$. Prominent dark clouds are labeled.

Molecular Cloud (see Fig. 1.1), but only because it is closer. At a distance of 140 pc, the entire region measures about 30 pc in linear extent. As before, we have labeled some of the main dark clouds, which show up as local peaks in the CO emission; Barnard's optical image is centered on L1521 and L1495. The dense core TMC-1 has been closely studied for its wealth of interstellar molecules. Shown also in Figure 1.9 is the famous star T Tauri, to which we shall return shortly. Note finally that the elongated structure to the north, including L1459 and L1434, and the high-intensity area to the west containing Barnard 5 (B5) and NGC 1333, are not physically associated with the Taurus-Auriga system, but are more distant, massive clouds seen in projection.

In passing from Orion to Taurus-Auriga, we have not only diminished the physical scale of the star forming region but also the mode of stellar production. The gas in Taurus-Auriga is *not* part of a giant complex; the total mass in molecular hydrogen is of order $10^4 M_{\odot}$. Nor is the region forming high-mass stars, with their attendent reflection nebulae and HII regions. Finally, the existing low-mass stars are nowhere clustered as densely as in the Trapezium or even the less populous groups of Orion B.

Let us now focus on the dark clouds of the region, using two different tracers. The upper panel of Figure 1.10 is a map of the central portion of Taurus-Auriga, covering TMC-1, TMC-2 and the dark cloud L1495 in Figure 1.9. The image shows emission from ${}^{13}C^{16}O$. This isotope



Figure 1.10 *upper panel*: Map of Taurus-Auriga in the 2.7 mm line of ${}^{13}C{}^{16}O$. *lower panel*: The same region as seen by IRAS. Here the brighter regions mark concentrations of relatively cold dust.

is excited at the same volume density as the more common ${}^{12}C^{16}O$. However, it effectively highlights regions of greater *column* density, which tend to trap the radiation from the more abundant species. Notice that the dark clouds have an elongated appearance, not unlike those in Orion (Figure 1.3).

As before, the infrared emission from warm dust grains is another useful tracer of molecular gas. The lower panel of Figure 1.10 is an IRAS map of the same region as in the upper panel. What is shown here is the ratio of the fluxes at 100 μ m and 60 μ m, a measure which emphasizes the contribution from the colder (near 30 K) grains. There is evidently an excellent match between the distributions of this dust component and the gaseous structures traced in ¹³C¹⁶O.

1.2.2 T Association

The dark clouds are also the birthplaces for young stars, as seen in Figure 1.11, which is a composite of radio (${}^{12}C^{16}O$), infrared, and optical data. For the stars, we have distinguished



Figure 1.11 Central region of Taurus-Auriga in ${}^{12}C^{16}O$, along with the locations of infrared stars (*squares*) and optically visible T Tauri stars (*triangles*).

deeply embedded sources seen here in the infrared from optically visible, low-mass objects. The latter belong to a class known as *T Tauri stars*, named for the prototypical object indicated in Figure 1.9. Stars of the T Tauri class are but one type of *pre-main-sequence* star. In regions like Orion, one also finds more massive pre-main-sequence objects known as *Herbig Ae/Be stars*. Finally, we have seen that Orion (but not Taurus-Auriga) contains a number of O and B stars, which are *main-sequence* objects. Note that a given source is classified as a T Tauri or Herbig Ae/Be star based on specific observational criteria, while the pre-main-sequence and main-sequence designations refer to the presumed evolutionary state of the star.

It is evident from Figure 1.11 that both the infrared and optically visible young stars of Taurus-Auriga are confined to the denser molecular gas. The same is true for Orion, but the stellar distributions are quite different. The Taurus Molecular Cloud harbors a *T* association, in which stars are spread out more uniformly. Although some degree of clumping is evident, we do not see the extreme crowding of Orion. Recall, for example, that the entire Trapezium Cluster shown in Figure 1.5 has a diameter of about 0.4 pc, while each of the sparser groupings in Figure 1.10 extends over about ten times that length.

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Figure 1.12 The dense core TMC-1C, as traced by the 1.3 cm line of NH_{3} .

The relative isolation of the young stars in Taurus-Auriga, together with the proximity of the region, have allowed more detailed study of individual stellar formation than in Orion. In particular, molecular transitions sensitive to higher densities than CO have been used effectively to examine the region's dense cores. Figure 1.12 is a radio map of TMC-1C, one of several subcondensations within TMC-1. The observations here were made in the 1.3 cm line of NH₃, which traces gas number densities near 10^4 cm⁻³. In central density, linear extent, and total mass, the Taurus-Auriga dense cores are similar to most of those traced by CS in Orion, but no very massive fragments are detected.

The dense core shown in Figure 1.12 does not contain a young star, but over half of those observed in NH₃ have infrared point sources in their central regions. These embedded objects represent an earlier evolutionary stage than the visible T Tauri stars. Interestingly, most of these infrared stars are associated with molecular outflows. Figure 1.13 is a CO map of the dark cloud L1551, which the reader may locate in Figure 1.9. The striking bipolar lobes represent cloud gas being dragged to great distances from the central infrared source, which in this case is an embedded binary pair known collectively as IRS 5. These stars, with a total luminosity of less than $30 L_{\odot}$, have a combined mass under $2 M_{\odot}$. In contrast, a high-mass star or group of stars is creating the outflow in the Orion BN-KL region. Discovered in 1980, the L1551/IRS 5 system was the first detected low-mass outflow, of which hundreds are now known. Indeed, the high frequency of outflow observations probably indicates that *every* star turns on a powerful wind before it is optically visible.

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The foregoing examples demonstrate amply that there is no difficulty producing a variety of stars in the present-day Galaxy, given the right conditions. Of course, part of our task is to elucidate what those "right conditions" are. Another goal must be to discern the sequence of events by which a rarified cloud actually condenses to the stellar state. Clearly, both efforts should be informed by a working knowledge of stars as physical objects and of the conceptual tools that have been developed for their study.



Figure 1.13 Map in ${}^{12}C^{16}O$ of the L1551 cloud in Taurus-Auriga. The star marks the position of the infrared source IRS 5.

1.3.1 Basic Properties

Virtually all the information we have about a star comes from the electromagnetic radiation it emits. Photons from the deeper layers break free and stream outward into space at the *photosphere*. The two most basic properties of the star are its luminosity, *i. e.*, the total energy emitted per unit time, and the temperature at the photosphere. When our focus is on the physics of stars, we will denote the luminosity as L_* , while the designation L_{bol} will be reserved for discussions of the emitted radiation. The latter notation emphasizes that we are interested in the *bolometric*, or total, luminosity, rather than that within a specific wavelength range.³ For the second variable, it is conventional to use the *effective temperature* T_{eff} , *i. e.*, the temperature of an equivalent blackbody of the same radius (see Chapter 2).

If the distance to the star is somehow known, L_{bol} can be obtained in principle by flux measurements over a sufficiently broad wavelength range. The temperature T_{eff} , on the other hand, must always be deduced through theoretical modeling. Accordingly, astronomers often prefer to characterize stars through two related quantities that are more easily measured. In place of L_{bol} , one may use the logarithmic quantity M_V , the *absolute magnitude* of the star in the V (for *visual*) band, a relatively narrow wavelength interval centered on 5500 Å. Suppose F_V is the flux received in this band, *i. e.*, the energy in a unit wavelength interval per unit area per time. This flux is weaker for objects that are farther away. To measure the *intrinsic* brightness, we imagine the star of interest to be located at some fixed distance, conventionally taken to be

³ We shall also use the symbol L_* when referring to the observationally estimated luminosity from the star alone, excluding any additional contribution from circumstellar matter. The quantity L_* is numerically identical to $L_{\rm bol}$ for mature stars that lack such material, but may differ in younger, more embedded objects.

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10 pc. Then M_V is defined as

$$M_V \equiv -2.5 \log F_V(10 \,\mathrm{pc}) + m_{V\circ} \,, \tag{1.1}$$

where $m_{V\circ}$ is a constant. Note that, by definition, fainter stars have numerically greater magnitudes. The V band used here is one of the standard Johnson-Morgan sequence of filters, which also include ultraviolet (U at 3650 Å) and blue (B at 4400 Å) wavebands. As detailed in Appendix A, another filter set, designated R, I, J, ...Q, extends into the infrared. Also used is the Strömgren four-color system. Here the filter sequence u, v, b, and y covers 3500 Å to 5500 Å.

Written in terms of an arbitrary wavelength λ , equation (1.1) becomes

$$M_{\lambda} \equiv -2.5 \log F_{\lambda}(10 \,\mathrm{pc}) + m_{\lambda \circ} , \qquad (1.2)$$

This equation can further be generalized to cover the case where the star is located, not at 10 pc, but at an arbitrary distance r. The new equation then defines a distance-dependent quantity known as the *apparent magnitude*:

$$m_{\lambda} \equiv -2.5 \log F_{\lambda}(r) + m_{\lambda \circ} . \tag{1.3}$$

Since the flux declines as r^{-2} , the apparent and absolute magnitudes are related by

$$m_{\lambda} = M_{\lambda} + 5 \log\left(\frac{r}{10 \text{ pc}}\right) ,$$
 (1.4)

where the term added to M_{λ} is the *distance modulus*.

To find a surrogate quantity for $T_{\rm eff}$, we take advantage of the fact that a star's surface temperature is correlated with its color. The latter can be quantified by forming the ratio of flux in the V band to some other, which is conventionally chosen as the B band. Equivalently, we define the B - V color index as $M_B - M_V$. Notice, from equation (1.4), that this quantity is also equal to $m_B - m_V$. We denote by $(B - V)_{\circ}$ the *intrinsic* color index. Here, the fluxes are not those directly observed, but calculated under the assumption that the path to the star is free of dust. These particles redden starlight and alter the apparent color (see § 2.3). The intrinsic index at two arbitrary wavelengths λ_1 and λ_2 is written C_{12}° . By convention, λ_1 is less than λ_2 .

The color index is a measure of surface temperature based on *photometric* observations, *i. e.*, those employing broadband filters. Another useful indicator is the *spectral type*. Astronomers evaluate this quantity by observing the relative strengths of sharp absorption lines in the spectrum. The sequence of spectral types in order of descending T_{eff} is designated O, B, A, F, G, K, and M, where the nomenclature has purely historical significance. Thus, the O stars that dominate the Orion Nebula are characterized by absorption lines from highly ionized heavy elements, such as C III (*i. e.*, C⁺⁺), O III, *etc.* On the other hand, the Taurus-Auriga region is rich in K and M stars, whose spectra show strong molecular bands in such species as CH and TiO. As a refinement of the system, each spectral type is further divided into ten subclasses, labeled 0 through 9, with higher numbers indicating cooler temperatures. The Sun, with its T_{eff} of 5800 K, is a G2 star. A star of type A0 serves to normalize the color indices. That is, the constants m_{λ_0} in equation (1.3) are selected so that the absolute magnitudes in all bands are identically zero for such an object.



Figure 1.14 Color-magnitude diagram for 1094 stars in the solar neighborhood.

1.3.2 Main Sequence

The single most powerful conceptual tool in stellar astronomy is the *Hertzsprung-Russell (HR)* diagram. This is a plot of luminosity versus surface temperature (or their equivalents) for a single star or stellar group. A plot of M_V versus $(B - V)_{\circ}$ is also known as a color-magnitude diagram, while the L_*-T_{eff} plane is often called a *theoretical HR diagram*. Figure 1.14 is a color-magnitude diagram for relatively nearby stars. The vast majority, including the Sun itself, lie along a band known as the main sequence. The Sun's location is shown by the large open circle at $M_V = +4.82$ and $(B - V)_{\circ} = +0.65$. Astronomers frequently refer to main-sequence stars as dwarfs, to distinguish them from the sparser group to the upper right, the giants. Also apparent is a group to the lower left, the white dwarfs.

Figure 1.15 shows the main sequence in the theoretical HR diagram. The existence of this locus, in either set of coordinates, reflects the basic physics of stellar structure. A star is a self-gravitating ball of gas, supported against collapse by its internal thermal pressure. Throughout its life, the star continually radiates energy from its surface at the rate L_* . In a main-sequence object, this energy is resupplied by the fusion of hydrogen into helium at the center. The quantity L_* thus equals, in this case, L_{int} , the luminosity crossing any interior



Figure 1.15 Evolutionary track of a 1 M_{\odot} star in the theoretical HR diagram. The grey solid line represents the zero-age main sequence (ZAMS), while the dashed curve is the birthline.

spherical shell (see Figure 1.16). A main-sequence star is therefore in both *hydrostatic* and *thermal* equilibrium.

In a star of given mass M_* and radius R_* , the condition of hydrostatic equilibrium necessitates a certain interior run of temperature and density, where both quantities decrease outward. The radiative energy flux across any shell depends on the local temperature gradient, so that L_{int} is also specified for this object. If we now imagine squeezing the star to smaller R_* , its interior density rises. So must the temperature, in order to counteract the greater self-gravity. The luminosity crossing interior shells will also increase in response to the steeper temperature gradient. On the other hand, the star's nuclear reaction rate, which reflects both the frequency and energy of proton collisions, has its own functional dependence on the central density and temperature. Thus, for each M_* , we cannot really vary R_* at will; there is only one value for which the interior luminosity can be sustained by reactions at the center. But the stellar radius connects L_* and T_{eff} through the equation

$$L_* = 4\pi R_*^2 \sigma_B T_{\rm eff}^4 . (1.5)$$

where σ_B is the Stefan-Boltzmann constant. This blackbody relation, which we derive in Chapter 2, actually *defines* T_{eff} . In summary, a main-sequence star of fixed mass has a unique L_* and T_{eff} . The curve in the HR diagram is simply the functional relationship $L_*(T_{\text{eff}})$ obtained by letting the stellar mass range freely.



Figure 1.16 Energy transport in a main-sequence star. The interior luminosity L_{int} is generated in the nuclear-burning region near the center and is equal to the surface value L_* .

1.3.3 Early Phases

For an object that is *not* fusing hydrogen, both L_* and $T_{\rm eff}$ change with time. Correspondingly, its representative point moves in the HR diagram. The fact that most stars are observed to be on the main sequence reflects the longevity of the hydrogen-burning phase, during which L_* and $T_{\rm eff}$ change only slightly. Younger objects are more distended, with central temperatures that are too low for maintaining the fusion reaction. Nevertheless, these pre-main-sequence stars are relatively luminous. Since they are also detectable at visible wavelengths, their properties are well studied.

What supplies the star's luminosity during this early phase? The answer is the compressive work of gravity, which slowly squeezes the object to higher density. The local rate of energy loss from this process is zero at the center and increases monotonically outward. Thus, as illustrated in Figure 1.17, L_{int} across an arbitrary mass shell within a pre-main-sequence star is *less* than L_* . The surface radiation now causes a net drain of energy, leading to steady contraction and to continuous alteration of both L_* and T_{eff} .

Determining pre-main-sequence tracks in the HR diagram for different stellar masses is an important aspect of star formation theory. Anticipating later results, Figure 1.15 shows the evolutionary track for a star of 1 M_{\odot} . The star first appears as an optically visible object on a curve called the *birthline*. As it then contracts, the star begins to descend a nearly vertical path. During this time, L_* is so high that energy is transported outward not by radiation but by *thermal convection*, *i.e.*, the mechanical motion of buoyant gas. By the time the star's path turns sharply upward and to the left, energy is partially transported by radiation, as well. After 3×10^7 yr, the star joins the main sequence.

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Pre-Main-Sequence Star

Figure 1.17 Energy transport in a pre-main-sequence star. In this case, there is no nuclear-burning region. The luminosity L_{int} monotonically increases from zero at the center to L_* at the surface.

Stars of other mass traverse analogous paths in the HR diagram but at very different rates. Less massive objects tend to have lower surface temperatures. According to equation (1.5), their values of L_* are also smaller for a given surface area, resulting in slower contraction. To quantify the rate, we first note that the sum of a star's thermal and gravitational energies is a negative quantity that is about GM_*^2/R_* in absolute value. The object radiates away an appreciable portion of this energy over the *Kelvin-Helmholtz time*:

$$t_{\rm KH} \equiv \frac{G M_*^2}{R_* L_*} = 3 \times 10^7 \,{\rm yr} \left(\frac{M_*}{1 \, M_\odot}\right)^2 \left(\frac{R_*}{1 \, R_\odot}\right)^{-1} \left(\frac{L_*}{1 \, L_\odot}\right)^{-1} \,.$$
(1.6)

The significance of $t_{\rm KH}$ is that the star shrinks by about a factor of two over this interval, starting from any point during its pre-main-sequence phase. Notice that $t_{\rm KH}$ gets *longer* as the contraction proceeds. Thus, equation (1.6) also provides an approximate measure of the *total* time needed for a star to contract to its main-sequence values of M_* , R_* , and L_* .

Figure 1.18 displays pre-main-sequence tracks over a wide range of masses. All tracks descend from the birthline, which intersects the main sequence near 8 M_{\odot} . Higher-mass stars exhibit no optically visible pre-main-sequence phase, but first appear on the main sequence itself. If we imagine a group of stars all beginning contraction on the birthline at t = 0, their subsequent positions in the diagram at any fixed time would fall along a sequence of smooth curves. Figure 1.18 also shows a set of such pre-main-sequence *isochrones*. The reader should verify that the pattern of isochrones is consistent with the slower evolution of less massive objects and with the continual slowing of contraction at any fixed mass.



Figure 1.18 Pre-main-sequence evolutionary tracks. Each track is labeled by the stellar mass in units of M_{\odot} . The grey curves are isochrones, labeled in yr. The t = 0 isochrone coincides with the birthline, the lighter solid curve at the top. Note that the $t = 1 \times 10^8$ yr isochrone nearly matches the ZAMS, the lighter solid curve at the bottom.

The pre-main-sequence phase of evolution is not the first. At an earlier epoch, stars are still forming out of the gravitational collapse of their parent dense cores. Such *protostars* are even more luminous than pre-main-sequence stars, but are so obscured by interstellar dust that their emitted radiation lies entirely in the infrared and longer wavelengths. Under these circumstances, $T_{\rm eff}$ cannot be found by the traditional methods. Indeed, the character of the observed spectrum reflects more the properties of the dust surrounding the star than the stellar surface. Protostars therefore cannot be placed in a conventional HR diagram, and their identification within molecular clouds is still not secure.

Returning to pre-main-sequence evolution, we noted earlier that the contraction of any star causes its central temperature to rise. As long as the stellar mass exceeds $0.08 M_{\odot}$, the temperature eventually reaches a value (near 10^7 K) where hydrogen fusion begins. Just at this point, the star is said to be on the *zero-age main sequence (ZAMS)*, and the corresponding relation between L_* (or L_{bol}) and T_{eff} marks a rather precise locus in the HR diagram. The ZAMS is the curve actually shown in both Figures 1.15 and 1.18, and its properties are also listed in Table 1.1. The reader should bear in mind that the table represents a one-parameter family, where

the basic physical variable is the stellar mass. Note also that astronomers sometimes use, in place of L_{bol} , the *bolometric magnitude*:

$$M_{\rm bol} \equiv -2.5 \log \left(\frac{L_{\rm bol}}{L_{\odot}}\right) + m_{\circ} , \qquad (1.7)$$

where the constant m_{\circ} is +4.75. The difference $M_{\text{bol}} - M_V$ for a main-sequence star of any spectral type is known as the *bolometric correction*, here evaluated in the V-waveband.

Mass	Sp. Type	M_V	$\log L_{\rm bol}$	$\log T_{\rm eff}$	$t_{\rm MS}$
(M_{\odot})		(mag)	(L_{\odot})	(K)	(yr)
60	05	-5.7	5.90	4.65	3.4×10^{6}
40	O6	-5.5	5.62	4.61	4.3×10^{6}
20	09	-4.5	4.99	4.52	8.1×10^{6}
18	B0	-4.0	4.72	4.49	1.2×10^{7}
10	B2	-2.4	3.76	4.34	2.6×10^{7}
8	В3	-1.6	3.28	4.27	3.3×10^{7}
6	B5	-1.2	2.92	4.19	6.1×10^{7}
4	B8	-0.2	2.26	4.08	1.6×10^{8}
2	A5	1.9	1.15	3.91	1.1×10^{9}
1.5	F2	3.6	0.46	3.84	2.7×10^{9}
1	G2	4.7	0.04	3.77	1.0×10^{10}
0.8	K0	6.5	-0.55	3.66	2.5×10^{10}
0.6	K7	8.6	-1.10	3.59	
0.4	M2	10.5	-1.78	3.54	
0.2	M5	12.2	-2.05	3.52	
0.1	M7	14.6	-2.60	3.46	

Table 1.1 Properties of the Main Sequence

1.3.4 Consumption of Nuclear Fuel

Stars remain on the main sequence for relatively long periods of time because of the vast supply of hydrogen available for fusion. To estimate the main-sequence lifetime $t_{\rm ms}$, we use the fact that the basic nuclear reaction is the fusion of four protons into ⁴He. This process releases 26.7 MeV per helium nucleus, or $0.007 m_p c^2$ for each proton of mass m_p . If f_H is the fraction of hydrogen consumed, then the star releases a total energy

$$E_{\rm tot} = 0.007 f_H X M_* c^2 \tag{1.8}$$

during this period. Here, X is the star's mass fraction in hydrogen, which is typically 70 percent. The energy E_{tot} divided by t_{ms} must equal the (nearly constant) luminosity L_* . Detailed calculations show that $f_H \approx 0.1$ for most masses, so that the lifetime is approximately ⁴

$$t_{\rm ms} \approx 5 \times 10^{-4} \, \frac{M_* \, c^2}{L_*} = 1 \times 10^{10} \, \frac{(M_*/M_{\odot})}{(L_*/L_{\odot})} \, {\rm yr} \; .$$
(1.9)

Here we have normalized the time to solar parameters. Because L_* increases very rapidly with M_* , $t_{\rm ms}$ falls correspondingly fast. Thus, the Sun, with a current age of 4.6×10^9 yr, is about midway through its main-sequence life. Table 1.1 gives more accurate values for $t_{\rm ms}$. We see that an O star of 40 M_{\odot} lives for a relatively brief time, only 4.3×10^6 yr, while a K star of $0.6 M_{\odot}$ burns hydrogen for 6.7×10^{10} yr, longer than the present age of the Galaxy.

As a star ends its life on the main sequence, its representative point in the HR diagram follows another well-defined path. Consider again the case of $1 M_{\odot}$, whose post-main-sequence track is shown by the dashed curve in Figure 1.15. The exhaustion of hydrogen leaves a heliumrich central region that is thermally inert, *i. e.*, too cold to ignite its own nuclear reactions. Surrounding this region is a thick shell of fusing hydrogen. Continued shell burning adds more helium to the core, which eventually contracts from its self-gravity and from the weight of the overlying envelope of matter. The energy released from this contraction expands the envelope, and the star moves rapidly to the right in the HR diagram. This period ends once the envelope becomes convectively unstable. The greatly distended star then moves up the nearly vertical *red giant branch*, which resembles a time-reversed pre-main-sequence track.

While ascending the giant branch, the star is characterized by a contracting, inert core of helium, a hydrogen-burning shell, and an expanding envelope. The energy from the core and shell raises the luminosity by a factor of almost 10^3 . The temperature in the core eventually reaches the point where helium can begin to fuse, forming ¹²C. The star then moves to the left in the HR diagram, tracing the *horizontal branch*. After another 10^8 yr, helium burning exhausts itself in the core and shifts to an outer shell. The star, now containing two burning shells, ascends the *asymptotic giant branch*, so called because it approaches the original giant branch.

The ultimate fate of a star depends on its initial mass. In the $1 M_{\odot}$ case, the asymptotic giant sheds a massive wind, exposing a small inert object at the center. The path in Figure 1.15 was computed under the plausible assumption that $0.4 M_{\odot}$ was lost during this phase. The remnant central star is a *white dwarf*, an object so dense that it cannot be supported by ordinary gas pressure. Instead, the outward force stems from electron *degeneracy pressure*, *i. e.*, the mutual repulsion of the electrons' quantum mechanical wavefunctions. Such a star has no nuclear reserves and gradually fades from sight along the dashed curve shown in Figure 1.15.

More massive stars repeat the core-shell pattern of nuclear fusion numerous times while traversing the upper reaches of the HR diagram. These multiple ignition events create successively heavier elements. There is a limit, however, to the energy that can be extracted this way. In stars more massive than about $8 M_{\odot}$, the central core eventually undergoes a violent collapse to become a *neutron star* or *black hole*. This collapse liberates so much energy that it completely disperses the outer layers of the star. Of the energy that is radiated, most goes into neutrinos.

⁴ In this book, the symbol \approx means "equals, to within a factor of two to three," while the symbol \sim means "equals, to within an order of magnitude."

Nevertheless, the optical luminosity associated with this *supernova* briefly exceeds that of the entire Galaxy. The neutron star or black hole left behind gradually dims, until its presence is only known through its gravitating mass.

1.4 The Galactic Context

This, in broadest outline, is the evolution of a single star. However, our theory has a global aspect as well, since stellar birth and death are part of a vast evolutionary scheme being enacted in all galaxies like our own. Although we will continue, throughout this book, to emphasize the more local aspects of the problem, it is important to bear in mind this larger picture. Accordingly, let us take a brief look at our Galaxy and the role of star formation within it.

1.4.1 Structure of the Milky Way

The most conspicuous feature of the Galaxy is its highly flattened *disk* of stars. Our Sun orbits at a radius of 8.5 kpc, or about a third of the distance to the outer edge. The local rotation speed is 220 km s^{-1} , corresponding to a period of 2.4×10^8 yr within this differentially rotating structure. The local thickness of the disk *i. e.*, the average vertical excursion of the stars within it, varies systematically with spectral type. Thus, O and B stars have a characteristic half-thickness of 100 pc, while the figure increases to 350 pc for G stars like the Sun.⁵ These observations refer to the *solar neighborhood*, *i. e.*, to objects closer than about 0.5 kpc.

The densest concentration of stars is in the *central bulge*. This nearly spherical configuration extends out of the disk plane and has a radius of 3 kpc. Even farther from the plane is an extended *stellar halo* (or *spheroid*) consisting of both *globular clusters* and a large population of field stars. Each cluster is a compact group with roughly 10^5 members. Halo stars, known collectively as Population II, are the oldest in the Galaxy, with only 1 percent or less of the heavy element content of those in the disk (Population I). The total mass of the stellar halo is at most comparable to that of the disk, about $6 \times 10^{10} M_{\odot}$. Finally, there is evidence for another nonplanar component, the unseen *dark halo*. The composition and spatial distribution of this (probably nonstellar) matter are still not known, but its total mass exceeds that of the disk and spheroid, perhaps by an order of magnitude.

What does the Galaxy look like? The solar system is embedded within the disk, so it is difficult to obtain a global view by direct observation, as opposed to theoretical reconstruction. While huge numbers of stars are visible at optical wavelengths, interstellar dust dims the light from the more distant ones. Hence, the effective viewing distance is limited to several kpc. However, red giant stars are relatively luminous and have such low surface temperatures that they emit copiously in the near infrared. Their radiation penetrates the dust and can thus be detected over much greater distances. The top panel of Figure 1.19 is a near-infrared portrait of the Galaxy obtained with the COBE satellite. Clearly evident in this remarkable image are the very thin disk and the central bulge. The bottom panel of the figure shows the more familiar, optical image.

⁵ We define the *half-thickness* Δz of a planar distribution of matter as one half the ratio of total surface density to the volume density at the midplane. Alternatively, one may specify the *scale height* h, defined as the location where the volume density falls to e^{-1} of its midplane value. For a Gaussian distribution of density, $\Delta z = (\sqrt{\pi}/2) h = 0.89 h$.



Figure 1.19 Two views of the Milky Way. The upper panel depicts the near-infrared emission, as seen by the COBE satellite. Beneath this is the optical image, shown at the same angular scale.

1.4.2 Spiral Arms

A true face-on view of our Galaxy is, of course, impossible to obtain, but would resemble the external galaxy M51 (NGC 5194), shown in the two panels of Figure 1.20. Here the most conspicuous feature is the presence of well-delineated *spiral arms*. Morphologically, M51 is a slightly *later-type* galaxy than the Milky Way, which has a somewhat larger nucleus and less extended arms. Other galaxies exhibit no spiral structure at all. Extreme *early-type* systems, the *ellipticals*, resemble three-dimensional spheroids rather than flattened disks.⁶ In addition, there is a motley crew of *irregulars*, typified by the small companion to M51 seen in Figure 1.20.

According to density wave theory, the arms in spiral galaxies are not composed of a fixed group of stars, but represent a wave-like enhancement of density and luminosity rotating at a characteristic *pattern speed*. Both stars and gas in the underlying disk periodically overtake the arms and pass through them. Notice that, in Figure 1.20, the arms are more evident in the left image, taken in blue light, whereas the central bulge shows up strongly in the righthand,

⁶ The designations "early" and "late," as applied to galaxies, refer to position along the Hubble morphological sequence. The same terms are used for stars, "early" ones being those with $T_{\rm eff}$ higher than solar. In neither case is there an implied *temporal* ordering.



Figure 1.20 The galaxy M51 seen in blue light (*left panel*) and through a red filter (*right panel*). Note the prominence of the spiral arms in the blue image.

near-infrared photograph. The color of a galaxy is determined by the relative abundance and distribution in spectral type of its component stars. O and B stars, which have the highest surface temperature, dominate the blue image, while red giants, *i. e.*, dying stars of relatively low mass, are better seen through the infrared filter. Apparently, the most massive stars are concentrated heavily in spiral arms.

Recall that the main-sequence lifetime of a typical O star is of order 10^6 yr, only about 1 percent of the rotation period of a spiral arm. Thus spiral arms must produce, at each location in the disk, a temporary increase in gas density leading to a rise in the local star formation rate. Although stars of all mass are formed, it is the exceptionally bright O and B stars that are most conspicuous in optical photographs. Once the spiral wave has passed, the rate of forming new stars drops back down to its former low level.

This picture is reinforced by looking at the *gas* content of spiral galaxies. As we have seen, the molecular clouds that form stars can be detected most readily through their emission in CO. Figure 1.21 is yet another view of the galaxy M51. Here, an intensity map in the 2.6 mm CO line has been superposed on an optical image in the red H α line, produced by atomic hydrogen heated to temperatures near 10⁴ K. It is clear that the molecular gas is indeed concentrated along the spiral arms. Note that the radio contours seen here represent only 30 percent of the total CO emission. The remainder emanates from the interarm region, but is too smoothly distributed to be detected by the interferometer used for this observation. Closer inspection reveals that the H α arms are displaced about 300 pc downstream from those seen in CO. Since H α mainly stems from O and B stars, the implication is that cold gas entering the arms first condenses to form large cloud structures that later produce the massive stars. For a representative velocity of 100 km s⁻¹ for material entering the arms, the corresponding time lag is 3×10^6 yr.



Figure 1.21 Map of M51 in the 2.6 mm line of ${}^{12}C{}^{16}O$ (*solid contours*) and the H α line at 6563 Å (*dark patches*).

1.4.3 Recycling of Gas and Stars

The total mass of Galactic molecular gas, from which all new stars originate, is estimated to be $2 \times 10^9 M_{\odot}$, or about 3 percent of the mass of the stellar disk. Much earlier in time, the very young Galaxy consisted entirely of diffuse gas. This material could have been produced cosmologically, during the nucleosynthesis occurring throughout the Universe in the first few minutes following the Big Bang. If so, the gas would have consisted solely of hydrogen, helium, and trace amounts of deuterium and lithium. On the other hand, both the present-day interstellar gas and the stars themselves, although composed predominantly of hydrogen and helium, contain a full complement of heavier elements, known in astronomical parlance as "metals." These could only have been produced through *stellar* nucleosynthesis. Thus, the primordial gas must first have condensed into stars, which later injected diffuse matter back into space. This gas itself had time to form a new generation of stars, which again injected gas following nuclear processing. The interstellar matter of today, therefore, has been recycled a number of times through stellar interiors.

Figure 1.22 illustrates the recycling process in a highly schematic fashion. Stars form continually through the condensation and collapse of interstellar gas clouds. These stars slowly consume their nuclear fuel, eventually ending their lives as white dwarfs, neutron stars, or black holes. The matter within such a *compact object* is irretrievably lost to the interstellar medium. But this mass is always less – often considerably less – than that of the original star, since stellar evolution itself inevitably produces mass loss.

1.4 The Galactic Context



Figure 1.22 Recycling of stars and gas in the Galaxy.

The mass ejection process from stars is gentle and protracted in those objects destined to become white dwarfs. As we have seen, the outer envelopes of such stars inflate greatly after exhaustion of the neutral hydrogen. The loosely bound envelope then escapes as a stellar wind during the red giant and asymptotic giant phases. As this expanding gas cools, heavy elements within it nucleate into interstellar grains, which are then dispersed along with the gas. Although we have already mentioned grains for their obscuration of starlight, we will have much more to say about these submicron-size particles, which play an important role in the formation of stars.

Frequently, the white dwarf that survives mass ejection is part of a binary system. In the course of its own evolution, the companion may drive off matter that lands on the high-density surface of the compact object. Once it is sufficiently compressed, this hot material undergoes runaway nuclear fusion; the resulting *nova* ejects additional matter into space. Finally, stars too massive to become white dwarfs emit strong winds throughout their relatively brief lifetimes. The dispersal of their outer layers in a supernova is yet another source of Galactic gas.

Of the three mechanisms described, winds from stars with $M_* \leq 3 M_{\odot}$ provide roughly 90 percent of the mass returned to the interstellar medium. Supernovae and the winds from massive stars account for the remainder. The latter two processes also yield the bulk of the heavy elements. All of the ejected gas mixes with that already present to form the raw material for new stars. The mixing process is partly nonlocal, since material from supernova explosions can be blown so far that it ultimately settles in a very different part of the Galaxy.

The formation of compact objects provides a continual drain on the Galactic gas content. Accordingly, the star formation rate has been falling with time for 1×10^{10} yr, the age of the oldest disk stars. This global formation rate, which we shall denote as \dot{M}_* , is currently about

 $4 M_{\odot} \text{ yr}^{-1}$. Here, the estimate relies on observations of O and B stars, which can be seen over the greatest distances. Using the known radiative output from a single star and the appropriate lifetime, the observed luminosity from a region yields the birthrate for stars of that type. The rate for all stars then follows by adopting a distribution of masses at birth. Another quantity of interest is \dot{m}_* , the *local* rate of star formation, as measured per unit area of the disk. Near our own Galactocentric radius ϖ_{\odot} , this quantity is about $3 \times 10^{-9} M_{\odot} \text{ yr}^{-1} \text{ pc}^{-2}$. The rate rises inward to a radius of about 3 kpc, inside of which it falls precipitously, before attaining a central peak. This behavior is correlated with the distribution of Galactic gas, and it is to this topic that we turn next.

Chapter Summary

The raw material for new stars within our Galaxy is a relatively small admixture of gas, concentrated especially near the spiral arms. Much of this diffuse matter is bound together into the extensive structures known as giant molecular clouds. At discrete sites, such as the Orion Nebula, both low-mass objects like the Sun and the much more luminous O and B stars form together within populous clusters. Other cloud complexes, such as that in Taurus-Auriga, are less dense and massive than giant molecular clouds. These sparser entities create loose associations of low- and intermediate-mass objects.

Each individual star originates in the collapse of a cloud fragment. After this optically invisible protostar phase, the subsequent evolution is conveniently pictured in the HR diagram, a plot of luminosity versus effective temperature. Starting at the locus known as the birthline, the star descends along a pre-main-sequence track, slowly contracting under its own gravity. The representative point in the diagram settles for a long time on the main sequence. Here the star derives energy from nuclear fusion. After exhausting this fuel, the object temporarily swells in radius, before eventually fading from sight. It also spews out gas, which joins the reservoir out of which additional stars will be made.

Suggested Reading

For an explanation of our abbreviations of journals and reviews, see the Sources list, toward the end of the book.

Section 1.1 The rich star-forming region of the Orion Nebula continues to yield fresh discoveries. Useful summaries, covering both the gas and stellar content, are

Genzel, R. & Stutzki, J. 1989, ARAA, 27, 41

O'Dell, C. R. 2003, *The Orion Nebula: Where Stars are Born* (Cambridge: Harvard U. Press).

Section 1.2 A brief but lucid summary of the Taurus-Auriga cloud complex and its stellar population is

Lada, E. A., Strom, K. M., & Myers, P. C. 1993, in *Protostars and Planets III*, ed. E. H. Levy and J. I. Lunine (Tucson: U. of Arizona Press), p. 245.

Section 1.3 Two texts on stellar structure and evolution are

Clayton, D. D. 1983, *Principles of Stellar Structure and Nucleosynthesis* (Chicago: U. of Chicago)

Hansen, C. J. & Kawaler, S. D. 1994, *Stellar Interiors: Physical Principles, Structure, and Evolution* (New York: Springer-Verlag).

As their titles imply, both books emphasize basic physics. Chapter 2 in the second text is a useful overview of the main phases of stellar evolution.

Section 1.4 The terminology used to describe the components of the Milky Way unfortunately varies among authors. Here we follow the convention established by

King, I. R. 1990, in *The Milky Way as a Galaxy*, ed. G. Gilmore, I. R. King, and P. C. van der Kruit (Mill Valley: University Books), p. 1.

Star formation on the Galactic scale will be treated more fully in Chapter 19. For general texts, we recommend

Binney, J. & Merrifield, M. 1998, Galactic Astronomy (Princeton: Princeton U. Press)

Scheffler, H. & Elsasser, H. 1987, *Physics of the Galaxy and Interstellar Matter* (New York: Springer-Verlag).

The first emphasizes Galactic structure, while the second also includes a very broad array of topics relevant to the interstellar medium.