Chapter 19: Star Formation
A Traumatic Birth

Outline

19.1 Star Forming Regions
19.2 The Formation of Sun-like Stars
19.3 Stars of Other Masses
19.4 Observations of Cloud Fragments and Protostars
19.5 Shock Waves and Star Formation
19.6 Star Clusters

Summary

The previous three chapters have introduced the interstellar medium, the stars themselves, the H−R diagram, a classification tool. Chapter 19 brings all of that information together under one topic, namely the stellar formation process. It begins by looking again at the various types of nebulae in which stars are believed to be forming. The contraction process is walked through from the triggering mechanism through protostar and finally to the main-sequence. Since most stars form as members of clusters, the chapter concludes with a discussion of various cluster types and explores methods of age determination using the H−R diagram.

Major Concepts

- Star formation
    - Gravity and Heat
    - Mass Dependence
    - Interstellar clouds
    - Protostars
    - Main sequence stars
    - Brown dwarfs
- Star clusters
    - Globular clusters
    - Open clusters
    - Associations

Teaching Suggestions and Demonstrations

Section 19.1

This first section picks up where the previous chapter left off. Chapter 18 discussed the various types of interstellar media and the birthplaces of stars while this and the following sections overview the products of the collapsing clouds.

Point out the importance of mass and, therefore, gravity, but remind the students that the temperature and rotational dynamics of the cloud are also critical players. Remind the students that temperature is a function of the motion of the individual atoms, molecules and particles. The higher the temperature, the more energy the atoms and molecules have with which to fight against gravity. It is almost ironic that in order to produce something as hot as a star, the initial cloud must be relatively cool.

Section 19.2

Stages in the **formation of a star like the Sun** are summarized in Table 19.1, which forms the basis for much of the discussion in this chapter. The dividing lines between most adjacent stages are not rigid; there is not an exact moment that a cloud fragment becomes a protostar, for instance. The evolution from protostar to actual star is more clearly defined: When core hydrogen begins fusing into helium, a star is born. It is now a main sequence star. ➲ **DEMO** The times given in Table 19.1 may be hard for students to relate to. You can create a timeline to compare the lengths of time the star spends at each stage. It should be obvious that the evolutionary process slows down as the star nears the main sequence portion of its life. Using a scale of 10^5 years equals one centimeter, the time for a star to evolve from stage 6 to stage 7 is three meters, whereas the time it takes to evolve all the way from the beginning to stage 5 is less than a third of a meter. To put star birth in the context of a star's life, point out that, using the same scale, the main sequence lifetime of our Sun would be represented by a kilometer!

The cloud that will eventually collapse to form stars must have the correct balance of density and size, as noted in the text. A large number of atoms are required to provide sufficient gravitational pull to attract a single atom. This concept may be described in terms used previously: temperature of a gas and the velocity of the atoms and escape velocity.
Imagine an atom at the edge of an interstellar cloud. The temperature of the gas determines the average velocity of the atom. This is given by

$$v = 115\sqrt{T} \text{ m/s}$$

where *m* is the mass of a hydrogen atom and *k* is the Boltzmann constant. This reduces simply to $v = 115\sqrt{T}$ m/s. In order for the cloud to collapse, the velocity of the atom must be less than the escape velocity. From previous discussions we know this to be

$$v_{esc} = \sqrt{\frac{2GM}{r}}$$

where *M* and *r* will be the mass and radius of the cloud. For a large cloud of 1000 solar masses and 10 pc radius (a density of 10 atoms per cm^3), as might be typically found, the escape velocity is 900 m/sec. Using this velocity to find the temperature gives T = 30 K. The temperature must be no more than 30 K for this atom to not escape. This and lower temperatures are found commonly in molecular clouds.

This same condition must be met at each stage of star formation. For the cloud fragment in stage 2, from Table 19-1, the total mass is about 3.5 solar masses and the size is about 0.03 pc (6700 A.U.) but the escape velocity is still about 900 m/sec and the surface temperature is still well below 30 K. Throughout the rest of the table, this condition continues to be met and by a wider and wider margin, i.e., the escape velocity becomes much larger than the velocity of the atoms. By stage 7 the diameter has decreased by a million from stage 2, so the escape velocity has increased by 1000. The temperature has increased by a factor of 60, but the gas velocity has increased by only about 8.

In a very basic approach to cloud collapse, the time it takes a single atom to fall to the center of the cloud (as the cloud collapses and neglecting all other effects) is known as the **free-fall time** and gives a rough idea of the length of time the process should take. Although there are various ways of calculating this time, here is a very simple approach. Let a cloud have a mass M and radius R. The acceleration due to gravity at its surface is

$$g = \frac{GM}{R^2}$$

This will not be constant but will vary strongly during the collapse as R changes. An average g can be used at $1/2R$, so

$$g = \frac{4GM}{R^2}$$

The distance x an object travels under a constant acceleration a in time t is

$$x = \frac{1}{2}at^2$$

In our case the distance will be R and a will be g, so

$$R = \frac{1}{2}gt^2$$

Putting in the expression for g and then solving for t gives

$$t = \sqrt{\frac{R^3}{2GM}}$$

For the initial cloud of 1000 solar masses and 10 pc radius, $t = 10^7$ years. This is approximately the right time scale of star formation. But it is easy to also see how this quickly breaks down as the star forms. If the calculation is repeated at stage 2, $t = 34{,}000$ years, which is much too small. Obviously the gas is not in free-fall after stage 2 and effects such as gas pressure become very important to the process of star formation.

The numbers in Table 19.1 can also be used with the radius-luminosity-temperature relationship from Chapter 17 to calculate the **luminosity** of the object at each stage. You can do this for stages 4, 5, and 6 and compare to the **evolutionary track** shown on the H−R diagram. Spend some time discussing the evolutionary tracks. Make sure students understand that the H−R diagrams shown in Chapter 17 represent data about temperature and luminosity for lots of different stars. Each star on a diagram is represented by one point. Furthermore, the main sequence shows a general relationship between a star's temperature and its luminosity but is *not* an evolutionary track. (A star does not move up or down the main sequence.) In the current chapter, the temperatures and luminosities of a single star at different points in its evolution are shown as a path or track "followed" by the evolving object.

From the discussion of blackbody radiation we know that the luminosity goes as the square of the radius and fourth power of the temperature. Using the surface temperatures and sizes given in Table 19-1 and converting to solar units we can calculate the luminosities at each stage in solar luminosities. Of course where in the spectrum this radiation will peak depends on the temperature alone (Wien's law). The following may be useful.

Stage	Luminosity	Peak Wavelength
1	34,000	0.3 mm
2	3	0.3 mm
3	3	0.03 mm
4	300	10,000 Å
5	9	7500 Å
6	0.6	6700 Å
7	1.0	5000 Å

These numbers are approximate but do reflect what occurs in Figures 19.5 and 19.7. It is immediately obvious from this table why infrared astronomy is so critical to the study of star formation. In stages 1 to 4, the forming star shines brightly in the infrared. Being embedded in a dusty molecular cloud would normally obscure it. But infrared can also pass through the dust of the cloud. The result is a view as shown in Figure 19.10.

Section 19.3

Section 19.2 focused primarily on stars of 1 solar mass. To broaden the scope, discuss figure 19.8, which shows the evolutionary track for a solar mass star plus one for a more massive star and a less massive star. Although details of evolution vary, as a general rule the more massive protostars evolve more quickly into more massive stars. In fact, it would be difficult for you to overstress the role played by mass. “It’s all about mass!” Mass drives everything from the gestation period to the lifetime on the main sequence to the luminosity to the form of a star’s death.

Why don’t brown dwarfs show up on the H−R diagram? This inevitable question usually serves as a springboard into discussions of the H−R and what it shows. The H−R diagram only contains stars that are or have been a main-sequence star; stars that, at one time or another, possessed a hydrogen fusion core. Recall that brown dwarfs lack the mass to produce this.

This is also a good time to resolve another point of confusion for many students. As a star ages, it may pass from one classification to another and would therefore be located at another position on the H−R diagram. This does not mean that the star will actually move from one place to another in space. Point out that the star itself cares not about how someone on an unknown tiny planet around an average star might characterize it.

Section 19.4

“How do we know how a star is born and evolves? Have we ever watched the process unfold before our very eyes?” This section provides observational evidence of various stellar birth processes in action. Show as many images of stellar nurseries as you can. Even though we cannot see the entire process in any one nursery, we can deduce the process by looking at many nurseries at once. The more of these that astronomers see, the more understanding they gain. Illuminate this idea by showing a photograph of a crowd of people. A few might be infants, many will be young and middle aged and a very small number might be more than 90 years old. Just because we cannot watch one individual age, we can learn a lot about the human aging process by examining many individuals in their various stages.

Section 19.5

This is your opportunity to foreshadow events to come for very massive stars. Sure, the collapse of a cloud can be triggered by such mundane things as a passing star or a reduction in the overall magnetic field, but the supernova explosion as a trigger for collapse is another thing all together. Although not necessarily the most common trigger, it is the most interesting for students. Show several images of supernova remnants such as the Crab Nebula in Figure 21.10 and the Veil Nebula in Figure 21.12. These are not only beautiful, but provocative in that they are the visible remnants of a dying star and at the same time provide the mechanisms for initiating stellar birth.

Section 19.6

Show slides or transparencies of **open clusters** and **globular clusters** to begin this final section of the chapter. Figure 19.18 (the Pleiades) and Figure 19.19 (Omega Centauri) provide excellent examples. Compare the two types of clusters with a chart that includes different characteristics. Let students suggest the first few entries by looking at the photos and pointing out obvious differences. Number of stars and general shape of cluster will probably be the first two entries. The presence or lack of gas and dust is another important distinction. Point out the reddish tint to the globular cluster (indicating old stars) as compared to the blue reflection nebula surrounding the young, hot stars of the Pleiades. A comparison of the H−R diagrams of the two clusters is also very informative. Because stellar evolution beyond the main sequence has not yet been discussed, ask students to hypothesize explanations for the truncated appearance of the main sequence of Omega Centauri.

Student Writing Questions

1. It is likely that the Sun, like other stars, formed as part of a cluster of stars. In what way might that environment have affected the formation of the solar system? For better or worse? Imagine the solar system forming in a very dense star cluster as opposed to a very loose star cluster. What might result from these two different situations that would eventually affect the structure of our solar system?

2. Pretend you could speed up the star formation process to one million years in one minute, from stage 1 through stage 6. Describe the events as you would see them and how long each would take. What would be the most action-packed event; the most boring event?

3. In this chapter, we see lots of stars forming throughout the Galaxy. Is it possible for this process to be stopped such that a cloud that might have formed a star is disrupted? What might those events be? Which stages of star formation might be most vulnerable to disruption? What will happen to the material in the cloud?

4. Along with star formation, planetary formation is presumably occurring, too. And it is upon planetary surfaces that life might eventually form. Trace the events experienced by an organic molecule, from its origin in the molecular cloud to its eventual destiny on the surface of a terrestrial-type planet. Are the chances good or poor for its survival? Is the planetary surface more protective or more deadly to this molecule than interstellar space?

5. Brown dwarfs are too small to be stars and too large to be planets. Why should astronomers be interested in them at all? Give as many reasons as you can think of why astronomers make such an effort to discover and study brown dwarfs.

Answers to End of Chapter Exercises

Review and Discussion

1. Star formation starts with an interstellar cloud of low density and temperature, tens of parsecs in diameter. It becomes unstable to gravitational collapse and starts to fragment. Tens, hundreds, even thousands of fragments are produced; each collapsing further, eventually to form a star. In a fragment, the collapse raises the central temperature to 10,000 K but the exterior remains cool and is able to radiate its energy. As the collapse continues, the central density and temperature increase and the object is known as a protostar. The protostar has a size hundreds of times larger than the Sun and a luminosity thousands of times larger, although its surface temperature is still relatively cool. The collapse slows and the luminosity of the protostar decreases, while the central temperature gradually increases. While still several times larger and brighter than the sun, the central temperature reaches 10 million K and hydrogen fusion begins. At this point it is finally a star. Continued slow contraction raises the central temperature to about 15 million K and the star finally becomes a main sequence star.

2. The temperature of the gas must be initially low enough so that the gas can gravitationally collapse. As it does, it radiates away its gravitational energy and does not heat up much. Then, as the cloud gets denser, radiation cannot escape so easily and the interior of the cloud starts to heat up. Slowly at first, and then ever increasingly, heat pushes against gravity and slows the collapse of the protostar. Gravity continues to compress the gas and heat it until finally the core temperature reaches 10 million K, which is sufficient to initiate hydrogen fusion. The object is now a star.

3. As an interstellar cloud collapses, it must spin faster as it conserves angular momentum. The cloud forms a flattened, rotating disk. The formation of the disk, in effect, concentrates the matter in the cloud, allowing it to eventually form a solar system.

4. As the interstellar cloud collapses, its gas is heated and becomes ionized, particularly toward the center of the cloud. The weak interstellar magnetic field gets concentrated during the collapse and can influence the ionized gases during the collapse. The magnetic field can be a stronger influence than gravity and can resist the force of gravity during the collapse, producing distortions in the cloud.

5. An evolutionary track is the “path” taken in the H−R diagram of the changes in a star. In this chapter the evolution is traced from birth to main sequence star. The track is simply a plot of the luminosity against the surface temperature and how it changes with time. Tracks are predicted by computer models and stars are observed at various stages along the track.

6. The large interstellar clouds in which star formation occurs are very massive. They fragment into small clouds, each of which eventually forms a star. Therefore a cluster of stars is formed rather than just single stars.

7. As the interior of the protostar heats up, it radiates more and more energy. The energy released tries to expand the star and works against the force of gravity that is collapsing the protostar.

8. High mass stars form much faster and are much brighter than lower mass stars during formation. Otherwise, the processes are very similar.

9. Brown dwarfs occur when a cloud fragment has insufficient mass to form a star. As the gas collapses and the core temperature increases, there is not enough gas to compress and heat the core to 10 million K. Hydrogen fusion never occurs and the object just radiates off its excess energy from formation. This is a brown dwarf.

10. T-Tauri stars occur at stage 4 in the formation of stars. It is a time when the protostar becomes less luminous as it shrinks and develops strong protostellar winds. The outer part of the protostar is shed in this wind.

11. Star formation takes place too slowly for astronomers to watch and follow over time. But astronomers have two other methods. First, they make computer models which can be changed rapidly with time. Second, there are very many stars in the sky and astronomers can try to locate stars at the various stages of formation and evolution. The observations are then used to further refine the computer models.

12. Radio and infrared observations are used in the study of star formation because the entire process occurs deep inside a molecular cloud, which itself is deep inside a dark, dense dust cloud. Visible light cannot escape from this environment but long wavelength radio and infrared can.

13. Protostars remain mostly hidden in dense dust clouds. Infrared observations have revealed these objects. Stars are more easily seen because of the visible light they emit and the clearing of the excess matter around the stars to reveal them.

14. A shell of gas, moving rapidly through space, builds up a thin sheet ahead of it of dense gas known as a shock wave. Shock waves can be formed by supernovae, spiral-arm waves, and HII regions from newly formed O and B stars.

    Shock waves are thought to be a trigger for star formation by helping collapse a normal interstellar cloud.

15. The H−R plots the changes in luminosity and surface temperature that occur during the various stages of star formation. This can then be compared to observations. Stages 1-3 cannot be plotted easily because the cloud is generally too cool to fall within the normal boundaries of the diagram.

16. The times are given in Table 19-1 and will not be repeated here. Evolutionary times are fast when the material is able to collapse under the influence of gravity. This collapse is slowed when the material becomes opaque to the flow of its radiation and the protostar forms an photosphere, after state 3. Upon further collapse, the interior gas is so hot that it pushes strongly outward, resisting the collapse by gravity, further slowing the collapse.

17. It appears that most stars form in clusters and associations. Since these groupings do not last long, whenever they are found we see relatively young stars.

18. Open clusters are young, with bright main sequence stars. Typically there are a few hundred to a few thousand stars. These clusters are found in the plane of the Milky Way. Globular clusters are very old, contain no bright main sequence stars but numerous red giants. They contain hundreds of thousands of stars and are found in the halo of the Milky Way.

19. The age of a star cluster is determined by the cut-off point of its main sequence. As stars evolve, more and more of the main sequence stars become red giants and die out, leaving only the fainter main sequence stars.

20. If a star cluster forms any O or B stars, they will completely evolve and die out before many of the lowest mass stars even evolve onto the main sequence. The HII region or supernova blasts from these massive stars can significantly affect further star formation, disrupting it in some places and initiating it in others.

Conceptual Self-Test

1. F
2. F
3. T
4. F
5. T
6. F
7. F
8. T
9. T
10. T
11. C
12. A
13. D
14. B
15. B
16. A
17. A
18. B
19. A
20. D

Problems

1. $v_{esc} = 11.2\sqrt{(1000 \times 330{,}000) / 10 \times 3.1\times10^{16} / 6.378\times10^{6}}$, $v_{esc} = 0.92$ km/s
   Half of this is 0.46 km/s. molecular speed = $0.157\sqrt{(10 / 2)} = 0.35$ km/s
   $v = 0.35$ km/s < 0.46 km/s
   With half the escape velocity higher than the velocity of the atoms, the condition is met for the cloud to contract.

2. Molecular speed = $0.157\sqrt{(1000 / 2)} = 3.5$ km/s.
   $v_{esc} = 11.2\sqrt{(M \times 330{,}000) / 3.1\times10^{16} / 6.378\times10^{6}}$, $v_{esc} = 0.092\sqrt{M}$
   $0.5 \times 0.092\sqrt{M} = 3.5$, $M = 5750$ solar masses.

3.

$$L = \left(\frac{1\times10^{6}}{2\times10^{8}}\right)^{2}\left(\frac{4500}{3000}\right)^{4}$$

$$L = 0.000127$$

This is a drop in luminosity by a factor of 7900. To find the magnitude drop, $m_1 - m_2 = 2.5\text{Log}(0.000127) = -9.7$, $m_2 - m_1 = 9.7$.

4. (a)

$$5000 = R^2\left(\frac{3500}{5780}\right)^4$$

R = 190 solar radii

(b)

$$3 = R^2\left(\frac{5000}{5780}\right)^4$$

R = 2.3 solar radii

5. Estimating the luminosity to be 10, 4.85 - m_2 = 2.5Log(10), m_2 = 2.3.

6. The main sequence star has a temperature of about 15,000 K. Since the luminosity is the same for both stars $(R_2/R_1)^2 = (T_1/T_2)^4$, $R_2/R_1 = (1/5)^2 = 1/25$. The 3000 K star is 25 times the size of the main sequence star.

7. Reading Figure 19.8, this mass star drops from about 10,000 to 5 solar luminosities. Using the magnitude formula from Chapter 17 gives $m_1 - m_2$ = 2.5Log(10,000 / 5) = 8.2.

8. The luminosity at stage 7 is one solar luminosity. The temperature is intermediate between 4500 and 6000 K, 5250 K. $1 = R^2(5250 / 5780)^4$, R = 1.2 solar radii.

9. Just put the radius and temperature into the *L-R-T* relationship. $L = 0.1^2 0.1^4$, $L = 10^{-6}$.

10. First, calculate the absolute magnitude of the brown dwarf, 4.85 - M_2 = 2.5Log(10^{-6}), M_2 = 19.8. Now use $m - M$ = 5Log(d) - 5 to calculate the distance in each case.
    (a) 18 - 19.8 = 5Log(d) - 5, d = 4.4 pc
    (b) 30 - 19.8 = 5Log(d) - 5, d = 1,100 pc = 1.1 kpc

11. The distance of 20 pc is converted to kilometers by multiplying by 3.1×10^{13} km/pc = 6.2×10^{14} km. Dividing by the speed of 5,000 km/s gives 1.2×10^{11} s = 3900 yrs.

12. Convert -8 into a relative luminosity, -8 = -2.5Log$L$, L = 1585. Five of these stars will have a combined luminosity of 7925. Converting back to a magnitude gives M = -2.5Log(7925), M = -9.75.

13. m - (-9.75) = 5Log(10^7) - 5, m = 20.25.

14. Use the velocity relationship from *More Precisely 2–3*, $v = \sqrt{GM/R}$. But since Earth has an orbital speed of 30 km/s, use solar-Earth units and this equation becomes $v = 30\sqrt{M/R}$. R = 2.5 pc = 516,000 A.U. and M = 1,000. Putting these into the equation gives v = 1.3 km/s.

    The circumference of the cluster is $2\pi R = 2\pi 2.5 \times 3.1\times10^{13}$ km = 4.9×10^{14} km. Divide this distance by the speed to get the period of the orbit, 4.9×10^{14} km / 1.3 km/s = 3.7×10^{14} s = 12 million years. In 500 million years, that is 42 complete orbits.

15. The force of gravity on a mass m at the tidal radius r, for this cluster is $F = G \times 20{,}000 \times m / r^2$. The tidal force due to the Galaxy, from Chapter 7 is $F_t = 2G \times 10^{11} \times m \times r / (8000)^3$.

Equating these two expressions and solving for r gives r = 37 pc.

Resource Information

Student CD Media

Movies/Animations
Bi-Polar Outflow
Evolution of a 1-Solar Mass Star

Interactive Student Tutorials
None

Physlet Illustrations
None

Transparencies

T-176	Table 19.1	Prestellar Evolution of a Solar-type Star	p. 493
T-177	Figure 19.4	Cloud Fragmentation	p. 493
T-178	Figure 19.6	Interstelar Cloud Evolution	p. 495
T-179	Figure 19.7/8	Newborn Star on the H-R Diagram and	p. 496
		Prestellar Evolutionary Tracks	p. 497
T-180	Figure 19.11	Protostars	p. 501
T-181	Figure 19.12	Protostellar Wind	p. 502
T-182	Figure 19.15	Generations of Star Formations	p. 504
T-183	Figure 19.17	Newborn Cluster	p. 506

Suggested Readings

Bartusiak, M. “Great Balls of Fire” Astronomy (November 2003) p. 49. Nice article overviewing some important historical developments in globular cluster observations. Nice images and discussion of aging techniques.

Djorgovski, S. George. “The dynamic lives of globular clusters.” *Sky & Telescope* (Oct 1998). p. 38. Describes the dynamics and evolution of globular clusters.

Fortier, Edmund A. “Dusty infant stars: a fine sight.” *Astronomy* (July 1997). p. 78. Gives directions for observing five nearby (within 500 light years) star clusters.

Frank, Adam. “Starmaker.” *Astronomy* (July 1996). p. 52. Describes accretion disks, jets, Herbig-Haro objects, and the role of angular momentum in star formation.

Jayawardhana, R. “Style and Substance.” *Astronomy* (December 2003). p. 42. Beautiful images and detailed discussion of many features in and around the famous Orion Nebula.

Kaisler, Denise. “Cosmic intrigue.” *Astronomy* (Oct 2000). p. 42. Describes the characteristics of globular clusters, their formation, and their role in determining the age of the universe.

Kanipe, Jeff. “The giant star pillars of M16.” *Astronomy* (Jan 1996). p. 46. Features images and a description of the star farming regions in the Eagle Nebula, M16.

Kurtz, Patti A. "One hot stellar nursery: NGC 604." *Astronomy* (Dec 1996). p. 46. Features an image and discussion of star formation in NGC 604, which is located in the Pinwheel Galaxy, M33.

Meylan, Georges; Brandl, Bernhard. "30 Doradus: birth of a star cluster." *Sky & Telescope* (Mar 1998). p. 40. Describes star formation in the nebula 30 Doradus.

Naeye, Robert. "No globular planets?" *Astronomy* (Oct 2000). p. 24. Reports on a search for planets orbiting stars in the globular cluster 47 Tucanae.

Meylan, Georges and Brandl, Bernhard. "30 Doradus: birth of a star cluster." *Sky & Telescope* (Mar 1998). p. 40. Describes star formation in the nebula 30 Doradus.

Pan, X., Shao, M., Kulkarni, S. "A distance of 133–137 parsecs to the Pleiades star cluster" *Nature* (22 January 2004) p. 326. A good example of the scientific process at work. Part of an ongoing debate about the satellite Hipparcos's determination of the distance to the Pleiades cluster. Interesting discussion of one method to deduce distance.

Pommier, Rod. "Seeking star clusters." *Astronomy* (May 2000). p. 84. An observer's guide to open clusters.

Ray, Thomas P. "Fountains of youth: early days in the life of a star." *Scientific American* (Aug 2000). p. 42. Gives an overview of the star forming process.

Stephens, Sally. "The excesses of youth: T Tauri stars." *Astronomy* (Sept 1996). p. 36. Describes the T Tauri phase of stellar formation.

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: