Chapter 1

How the Sun Came to Be: Stellar Evolution

It was not until about 1600 that anyone speculated that the Sun and the stars were the same kind of objects. We now know that the Sun is one of about 100,000,000,000 (10^{11}) stars in our own galaxy, the Milky Way, and that there are probably at least 10^{11} galaxies in the Universe. The Sun seems to be a very average, middle-aged star some 4.5 billion years old with our nearest neighbor star about 4 light-years away. Our own location in the galaxy is toward the outer edge, about 30,000 light-years from the galactic center. The solar system orbits the center of the galaxy with a period of about 200,000,000 years, an amount of time we may think of as a ***Sun-year***. In its life so far, the Sun has made about 22 trips around the galaxy; like a 22-year old human, it is still in the prime of its life.

Section 1.—The Protostar

Current theories hold that about 5 billion years ago the Sun began to form from a huge dark cloud of dust and vapor that included the remnants of earlier stars which had exploded. Under the influence of gravity the cloud began to contract and rotate. The contraction rate near the center was greatest, and gradually a dense central core formed. As the rotation rate increased, due to conservation of angular momentum, the outer parts began to flatten. Some of the dust and vapor near the outer edge of this disk formed smaller condensations, each spinning around its own center in the same direction as the parent cloud. These were destined to become Earth and the other planets of our solar system.

Many stars, at this early stage of their evolution, split into two or three parts, resulting in ***binary star systems*** or multiple star systems. At least two-thirds of the stars we have observed are binary or multiple star systems, but it is not yet known whether stars routinely form planets as our star did. No other planetary systems have yet been observed, due to the great difficulty of seeing dark, small planets at great distances, but it is suspected that large numbers of planets do exist and that conditions suitable for life could be found on these planets. The moon systems of Jupiter and the other giant planets resemble a miniature solar system and thus provide further support for the idea that planetary systems may form rather easily.

The contracting cloud began to heat up, to glow and to exert pressure that counteracted the gravitational in-fall. This glowing core was now a ***protostar***, surrounded by dust and vapor. Had we been able to see it from our present location, the protostar would be quite dark, emitting only a small amount of infrared radiation from its core. The sun stayed in this cocoon-like state for about 10,000,000 years until its true stellar birth. While the protostar slowly radiated its energy away, the pressure in the hot core decreased, allowing the core to continue its collapse. The temperature increased until it became so hot that the first nuclear reactions were ignited.

Section 2.—The Hydrogen Burning Stage

With the start of nuclear reactions in its core, the Sun began its life as a true star, heated not by the meager energy of gravitational collapse but by the nearly inexhaustible supply of nuclear fuel contained in its vast interior. This nuclear furnace has maintained the Sun in a state of near equilibrium, producing just enough heat and pressure to counteract the crushing inward force of gravity and stop the contraction.

The Sun has remained in this stable state for the last 4.5 billion years, but what of its future? The Sun is slowly getting brighter (higher luminosity) and larger, while its rotation rate is slowing. It is believed that the young Sun was only about 70% as bright as it is now; and it had an equatorial rotation period of about 9 days, rather than 27 days as it now has. This higher rotation rate probably caused more eruptive activity on the surface. Overall, the Sun seems to be quieting down in its level of turbulence and eruptive activity; at the same time it is increasing in temperature, luminosity and size. It is predicted that in about 1.5 billion years, when the Sun is 6 billion years old, it will be about

15% brighter than it is at present. By the time the Sun is 10 billion years old, it will be about twice as bright as it now is and have a radius about 40% greater (Figure 1–1).

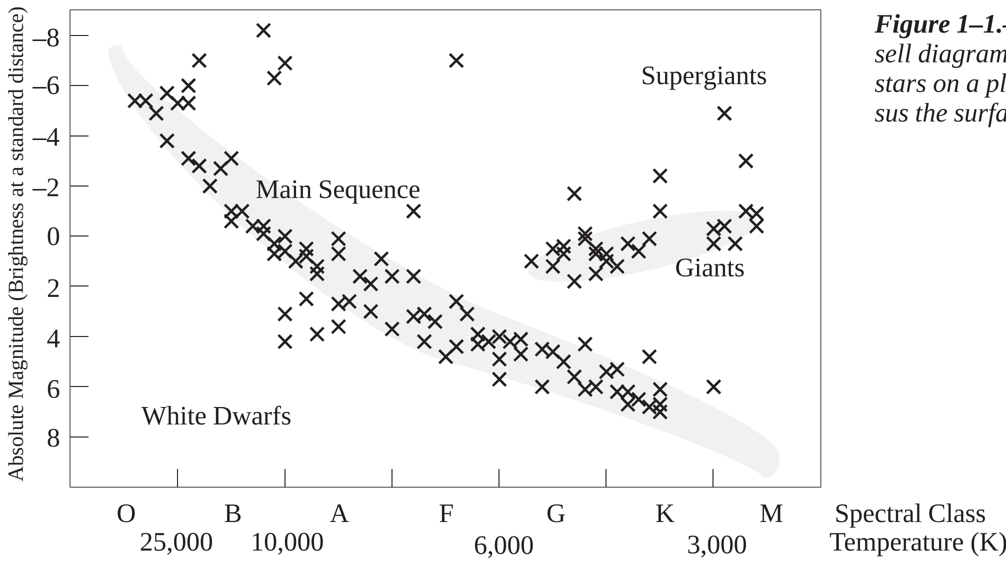

Figure 1–1.*—A Hertzsprung-Russell diagram showing selected stars on a plot of luminosity versus the surface temperature.*

Section 3.—Becoming a Red Giant

During the first phase of a star's life, the nuclear furnace at the core fuses hydrogen nuclei into helium nuclei. After about 10 billion years the hydrogen fuel in the core will be exhausted and the core will begin to contract again (Figure 1–2). This will cause a rise in temperature, and hydrogen fusion will begin in a shell surrounding the core. The surface

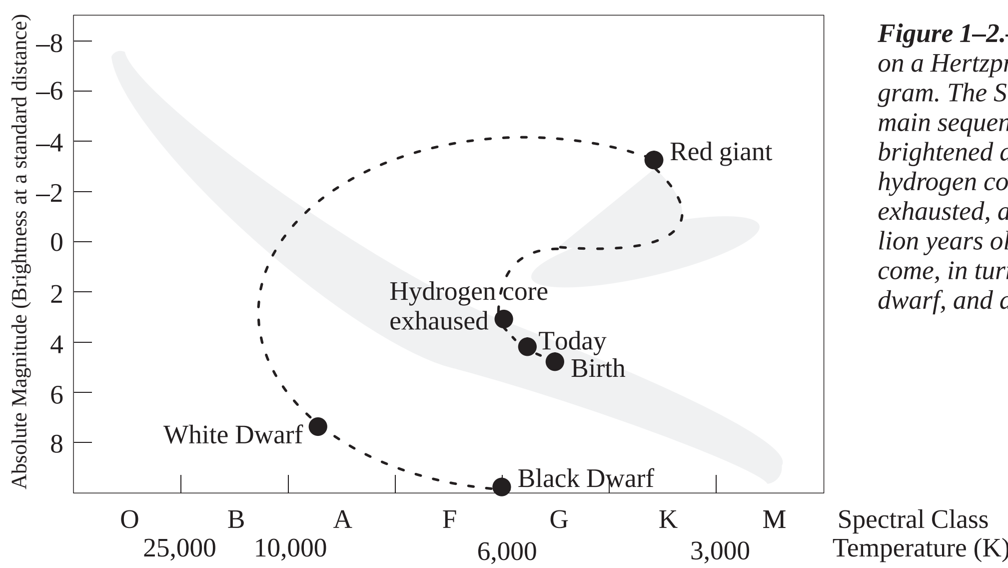

Figure 1–2.*—The life of the Sun on a Hertzsprung-Russell diagram. The Sun was born on the main sequence and has since brightened and cooled. The Sun's hydrogen core will eventually be exhausted, after the Sun is 10 billion years old. The Sun will become, in turn, a red giant, a white dwarf, and a black dwarf.*

layers will expand for the next 1.5 billion years until the Sun is 3 times its present size. An observer on Earth would see the Sun as a bright-red disk, 3 times the size of a full Moon. However, the presence of such an observer is doubtful, for the luminosity will be 3 times greater than it is now, and the Earth will be 100 K hotter than at present.

The Sun will keep expanding in size and luminosity, becoming a ***red giant*** star. Its radius will reach 100 times its present size, so that the planet Mercury will be engulfed and vaporized. Its luminosity will be 500 times the present value, causing Earth's surface to become a sea of molten lava at a temperature of about 1700 K. The Sun will remain in this red giant stage for a mere 250 million years (about 1 Sun-year), while its core contracts and heats up. When the core temperature reaches about 100 million K, the helium ash remaining from the earlier stages of nuclear fusion can begin to fuse into carbon. This will release huge amounts of energy and raise the core temperature to about 300 million K. The ignition of helium fusion is a sudden and explosive event known as the ***helium flash***. As much as one-third of the Sun's mass will be hurled out into space, forming a ***planetary nebula***. The core then will cool to about 100 million K, where it will begin the steady burning of helium. By then it will be about 10 times its present diameter and have 20 times its present luminosity.

Section 4.—Dwarfs, Neutron Stars, Supernovas, and Black Holes

After the supply of helium is converted into carbon, the remaining mass of the Sun will shrink and cool into a ***white-dwarf star***. It will then be about 15 billion years old, only 1% of its present size (about the size of Earth), and 0.1% as luminous. The white-dwarf, made entirely of carbon nuclei, will be incredibly dense; about half the present solar mass will be squeezed into a sphere the size of Earth. This density, about 2×10^9 kg/m^3, is roughly what would result if several 1000 kg automobiles were compacted to fit into a thimble. Gradually, over several billion more years, the white-dwarf will decrease in temperature and luminosity and end its life as a cool, dark cinder of carbon known as a ***black dwarf***.

All stars do not become black dwarfs. This end is predicted for smaller stars, with masses of up to about 3 solar masses; larger stars burn through their supply of hydrogen and helium relatively quickly. When the helium is exhausted, the inevitable collapse of the core raises the temperature high enough that fusion of heavier elements can occur. Eventually, the first 26 elements, up to iron, are produced. There is no way for thermonuclear fusion to continue beyond iron. As the core clogs up with iron, the star cannot generate more energy. With no pressure to counteract the effects of gravity, a third collapse begins, and eventually electrons and protons are forced together to form neutrons. The star finally stabilizes and ends its life as a small ***neutron star***, only about 16 km in diameter and with a density on the order of a billion billion kg/m^3.

In even larger stars, the collapse of the iron-filled core happens so rapidly that the star literally tears itself apart in a massive explosion known as a ***supernova***. This is the most spectacular stellar event known. For several days the star emits more energy than an entire galaxy . During the supernova, temperature and pressure are so high that all of the elements up to uranium and plutonium are created and then hurled out into space. It is believed that in the early history of the universe, many large stars formed, became supernovas, and synthesized all of the known elements. These elements were then incorporated into new generations of stars, some of which became supernovas and formed more heavy elements. This process occurs repeatedly so that the concentration of heavy elements in the universe continues to increase. Within the Sun we can see traces of all of the elements, and it is presumed that everything heavier than iron was formed previously in a supernova.

During the supernova process, the core of the star is crushed into a mass of neutrons. The remaining neutron star is only about 16 km across and spins rapidly on its axis, typically 20 to 50 times per second. The star's original magnetic field has been concentrated by the collapse and is now extremely strong. Electrons spiraling in toward the north and south magnetic poles of the rotating star produce radio waves in a narrow beam that flash out from the magnetic poles of the star. As the star spins, this beam acts like the beam of a beacon light similar to the flashing light on top of a police car. When these pulsating radio signals were first detected on Earth in the 1960s, it was thought that they might be coded signals from some intelligent life form, and the objects were humorously referred to as LGM (little green men). We have now detected more than 500 of these rotating neutron stars, known as ***pulsars***.

The most massive stars are thought to have an even stranger fate. Because of the very large mass and associated gravity, the final collapse of the star cannot be stopped. The star collapses into itself and forms a ***black hole***. The nature of space and time near a black hole is not fully understood, but mathematical models have been developed which suggest that there are several types of black holes; as yet, a black hole has not been definitely observed. The concept of the black hole goes back to at least 1783, when John Michell speculated on the existence of a star with such strong gravity that no light could escape from it. Astronomers have now detected several dark regions of space that emit x-rays. It is thought that these x-rays are produced as electrons accelerate into a black hole. It is interesting to speculate about where matter goes after it disappears into a black hole. Some scientists believe that the black hole can eventually fill up and return as normal matter, while others have suggested that perhaps a black hole has another side, a white hole, where matter spontaneously appears in space. Perhaps the black hole is a portal to another universe, or a shortcut to a distant location in our own universe (a wormhole). It has been theorized that strange things like these may exist near the center of galaxies.

Much of our knowledge of stellar evolution—the birth, life and death of stars—is based on observations of the Sun. For astrophysicists, the Sun is a magnificent laboratory for the detailed study of stars. But as we have looked more closely at the Sun over the last few decades using space-based instruments, a complex and mysterious picture has emerged. The turbulent surface atmosphere that we observe, with its contorted and dynamic magnetic field structures, is still highly unpredictable. Although we know more about the Sun every day, there are many unanswered questions, and new ones arise constantly.

Problems and Questions

1. (a) How many stars are in our galaxy and how is it possible to estimate this number? How accurately is this number known?

   (b) About how many galaxies seem to be in the universe?

   (c) How long would it take to count up to this number at the rate of one number per second?

   (d) About how many stars are in the universe?

   (e) Estimate the mass of all the stars in the universe.

2. Explain what a Sun-year is and why we say that the Sun is now about 22 years old. How many years old will the Sun be:

   (a) when it exhausts the hydrogen fuel in the core?

   (b) when it becomes a red giant and engulfs Mercury?

   (c) when it is a white dwarf?

3. Notice that Figure 1–2., showing the life of the Sun on a Hertzprung-Russell diagram, does not have a time axis. How could time be shown?

4. Assuming that the proto-solar nebula had uniform density out to 5 AU (Jupiter's present orbit) and rotated with a period of 12 years, find the new rotational period as the sun collapsed to its present size. Hint: use conservation of angular momentum.

5. (a) What elements are present in the Sun and in roughly what proportions?

   (b) What elements can be formed by the nuclear fusion processes inside the Sun, a small star?

   (c) What elements can be formed inside larger stars?

   (d) How are elements heavier than iron formed?

6. What are the possible ways that a star can end its life?