Chapter 6

The Sun as a Star

In This Chapter

- The Sun formed from gas and dust
- The Sun is mainly made of hydrogen
- The Sun is a star
- We learn what the Sun is made of from its spectrum

Annie Oakley sang, in the Irving Berlin musical *Annie Get Your Gun*, "I've got the Sun in the morning and the Moon at night" and "moonlight gives me the Milky Way." In fact, the stars in the Milky Way are distant suns, and our Sun is just a close-up of what many of the distant stars look like. Let's discuss how the Sun got to be as it is and how it compares with other stars.

Presto, the Sun

On a dark night, far from city lights, you can see a faint band of brightness arch across the sky. This Milky Way becomes more apparent to the eye the longer you are outside, shielded from lights that ruin your night vision. The Milky Way we see is composed of billions of stars as well as gas and dust between the stars. The processes that formed our Sun are still going on, and new stars are forming all the time.

About five billion years ago, a cloud of gas and dust began to fall together. Gravity is always pulling everything toward everything else, and perhaps some random fluctuation in the cloud of gas and dust made it denser than its surroundings. Once gravity starts pulling gas and dust together in this way, very little can stop the free fall.

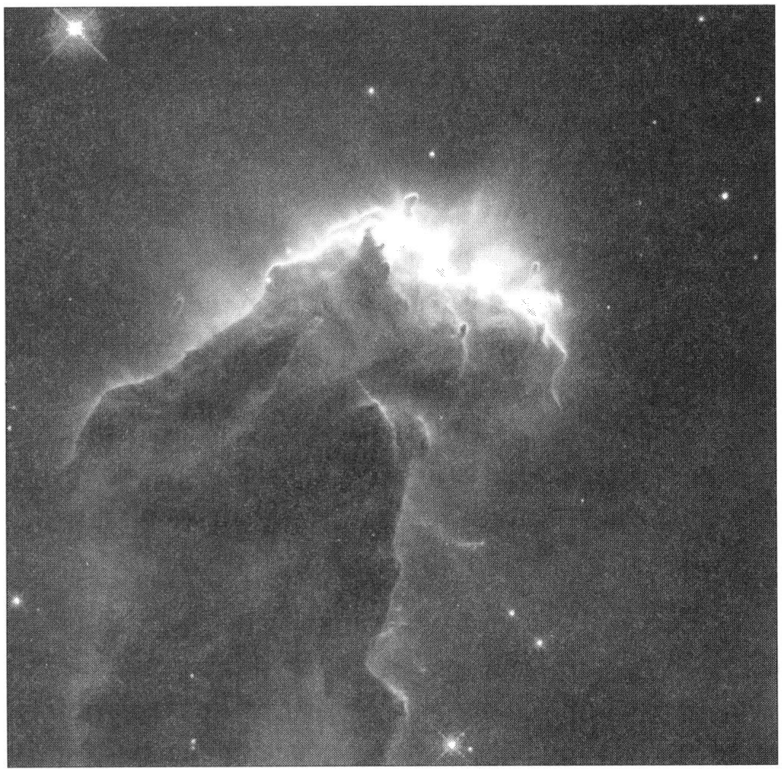
How did it all begin? Maybe a cloud of gas and dust started out randomly to form the Sun, but maybe a supernova nearby in space started the collapse. Astronomers find some radioactive aluminum that may be left over from that supernova. The question is controversial.

When you take a random cloud of gas and dust, it may have a little spin in some direction. It would be odd if it were completely not spinning. When something that is spinning collapses, it spins faster. The principle involves a concept called angular momentum. The amount of angular momentum that a system of matter has depends on how fast it is spinning and how far the various spinning parts are from the central axis. The faster something is spinning or the farther spinning parts are from the axis, the higher the amount of angular momentum is.

The amount of angular momentum that any system has remains constant, unless some outside force changes it. A merry-go-round doesn't just stop abruptly. Brakes and gears have to slow it down, and they apply outside forces that stop the merry-go-round's spin.

As the solar system collapsed, it had to spin faster because its various parts were closer to its axis. The process defines directions in the spinning cloud: along the axis or perpendicular to the axis. Along the axis, there is no spin, and the cloud simply continues to collapse, getting smaller and smaller. But perpendicular to the axis, the matter goes around and around the axis in circles or ellipses. Let us consider matter in a flat plane perpendicular to the cloud's axis of spin. Its forward momentum tends to keep the matter going straight ahead, even while gravity is pulling it inward. Being thrown forward by the forward momentum keeps the matter from collapsing as fast. We often say that "centrifugal force" is throwing things outward, but physicists accurately say that there is really no such thing as centrifugal force. It is a fake force, just acting as an explanation for why things don't move inward as fast as you might expect without considering everything's inertia from forward motion.

We can think of the cloud of gas and dust as a set of spinning disks. The disks from the top and the bottom are being pulled by gravity toward the central disk. But the disks themselves don't collapse as fast. Within each disk, since its angular momentum doesn't change, it spins faster as it gets smaller.



A Hubble Space Telescope view of part of a cloud of gas and dust known as the Eagle Nebula. Stars are forming inside its pillars, one of which is shown here. The pillars are known as EGGs, or Evaporating Gaseous Globules. Radiation from the new stars forming at their tips evaporates the material that has shielded them long enough to allow them to form inside the cocoons of dust.

(Jeff Hester and Paul Scowen, ASU and NASA)

Fun Sun Facts

The concept that angular momentum doesn't change affects not only the solar system, but also ice skaters. If you watched Sarah Hughes's gold-medal performance at the 2002 Winter Olympics, you could see that she started each spin with her arms outstretched. Then she pulled her arms inward to make herself spin faster. The laws of physics were making her spin faster to keep the amount of her angular momentum constant. Because her body parts were closer to her axis of spin, she had to be spinning faster.

We wound up with a spinning disk of gas and dust. The central region had the most material and became hotter as energy was released from the force of gravity. This hot gas in the center became hot enough for nuclear fusion to begin. At that instant, the Sun was born.

In the disk around this young Sun, clumps of gas and dust themselves began to coalesce. We say that they became planetesimals. Eventually, the planetesimals began to clump into larger objects. The largest of these objects are the planets.

The young, hot Sun threw off particles into space. They expanded outward in a fierce "solar wind." This solar wind tore away most of the gas and dust in the inner part of the solar system. The energy from the young Sun heated the rest and evaporated the dust. We were left, about five billion years ago, with the solar system we know: a shining Sun at the center with planets orbiting it.

Whither the Sun

When we manage to measure how many atoms of each type there are, the answer is somewhat surprising. Though we on Earth see lots of silicon in the rocks and iron in other objects and breathe air that contains mainly nitrogen and oxygen, these elements make up together less than 1 percent of the atoms in space. It turns out that about 90 percent of the atoms in space are hydrogen, another 9 percent or so of the atoms are helium, and all the other 100-plus types of atoms make up less than 1 percent.

What are these elements? They are made of subatomic particles called protons, neutrons, and electrons. Each atom is made of a nucleus with a positive charge surrounded by electrons that have negative charges. We ordinarily think of atoms on Earth as being in a neutral state. They have as many negative charges as positive charges, so they are electrically neutral. The nucleus has as many charges in it as it has protons. The neutrons in the nucleus, as their name implies, are neutral.

In many places in the universe, the atoms are not whole. An atom that has lost one or more electrons is called an *ion* (pronounced *eye'on*). An atom that has lost one electron is "once ionized." An atom that has lost two electrons is "twice ionized," and so on. The hotter a gas is, the more of its atoms are ionized.

In the center of the Sun, the atoms are completely ionized. The nuclei and the electrons are floating freely. A gas that is ionized like this is called a *plasma*, not to be confused with the plasma in human blood. Most of the universe is made up of plasma. Often people speak of three states of matter: solid, liquid, and gas. Informally, plasma is sometimes called a fourth state, though it is really a type of gas. We often distinguish plasma because its components have electric charges. Therefore, they can be bent by magnetic fields.

Sun Words

An **ion** is an atom that has lost one or more of its electrons. A **plasma** is a gas composed of ions and the electrons that balance the charge.

The simplest element is hydrogen. Ordinary hydrogen has just one proton. In a neutral hydrogen atom, that proton is surrounded by one electron. In the center of the Sun, when we talk of hydrogen, we really mean that proton alone.

Protons are about 1,800 times more massive than electrons, so the nuclei dominate the masses of atoms. Neutrons have about the same masses as protons, though they have no electric charge. Only certain combinations of protons and neutrons are stable.

A certain form of hydrogen contains not merely one proton, but also one neutron. This type of atom is called heavy hydrogen or deuterium. The nucleus itself is called a deuteron. It is very stable, and about 1 part in 6,000 of all the hydrogen atoms in the oceans on Earth are deuterium.

Fun Sun Facts

Since deuterium undergoes fusion at lower temperatures than ordinary hydrogen, many scientists look toward deuterium as the fuel for fusion reactors. The fuel would then be obtainable cheaply from ocean water. Research on building such reactors, though, is such that power from fusion is about 50 years away. Cynics say that power from fusion has long been and always will be about 50 years away.

A third form of hydrogen, known as tritium, combines two neutrons with one proton. Tritium is not stable; after some time, it spontaneously disintegrates. We say that it is radioactive, a word coined by Marie Curie about 100 years ago. Her thesis on radioactivity led to the first of her two Nobel Prizes, which she shared with her husband, Pierre (and with Henri Becquerel).

When an atom has two protons instead of one, it is helium instead of hydrogen. Stable forms of helium exist with one or two neutrons. Helium-3 has two protons and one neutron, while helium-4 has two protons and two neutrons. Helium-4 is the ordinary and dominant kind.

Such variations among the elements, with a fixed number of protons but different numbers of neutrons, are called *isotopes*.

In the first 3 minutes or so after the Big Bang, some 15 or so billion years ago, hydrogen (including some deuterium) and helium were formed, along with very small amounts of the lightest elements like lithium. Carbon, oxygen, and other heavy elements up to iron are formed in stars. The heaviest elements are formed in stellar explosions, as we shall see later in Chapter 10.

Sun Words

Isotopes are forms of atoms with different numbers of neutrons; the neutrons add mass but not charge. For example, the most common isotope of hydrogen has just a proton, and another isotope of hydrogen is deuterium, which has a proton plus a neutron.

When the Sun formed, it incorporated the gas in space, which was 90 percent hydrogen, 9 percent helium, and less than 1 percent everything else. Deep inside, it is now cooking some of its hydrogen into helium. As we saw in the previous chapter, energy results and makes the Sun shine. At the rate that this process happens, the Sun is about halfway through its 10-billion–year lifetime.

Fun Sun Facts

In 1929, the young Harvard astronomer Cecilia Payne's study of spectra showed that most of the gas in the atmospheres of stars is hydrogen. This was a surprising result and was so novel that Payne was pressured not to publish it. It took a few more years—and work by such people as Henry Norris Russell and Donald Menzel—to verify Payne's results. Payne, using her married name of Cecilia Payne-Gaposchkin, went on to later triumphs. For the last few years, there has been much discussion of whether her gender impeded her recognition for her discovery. In any case, she is now widely acknowledged as the pioneer.

The actual process that fuels the Sun is known as the proton-proton chain. In it, two protons interact to form a deuteron. Then the deuteron interacts with another proton to form helium-3. At the same time, an adjacent helium-3 is being formed out of a deuteron (again formed out of two protons) and a proton. Six protons in all have gone into this mix. Then the two helium-3s combine, and the result is helium-4 plus two protons. Though the mass is about six times the mass of a proton, it is slightly less than the total mass of the six protons that went into the element formation. The difference in mass is released from the atom in a quantity measured by $E = mc^2$, the formula discovered by Albert Einstein as part of his special theory of relativity in 1906. In the previous chapter, we saw how the discovery of neutrinos from the Sun, which led to the Nobel Prize in Physics in 2002, has verified this proton-proton chain.

The other elements in the Sun are measured in a couple of ways. Examination of the Sun's spectrum is a major method. The telltale fingerprints of almost all the different elements can be found in the solar spectrum and can be analyzed to tell the quantities (abundances) of the elements. Another way is to study meteorites, rocks of stone or iron/nickel that land on Earth. They can be analyzed in laboratories, and the abundances of the elements can be measured relative to each other. Though the hydrogen and helium have escaped from the meteorites, the results for the other elements agree.

The Sun Is a Star

When you examine the rainbow of color from the stars, using a telescope and a device called a spectrograph, the resulting spectra have telltale differences. Overall, however, the spectra we get from the stars are similar to the spectrum we get from the Sun, though they are much less bright. Even the brightest star is 10 billion times fainter than the Sun.

The spectrum of each star, the Sun included, is a rainbow of color crossed by some gaps in the color. (See page 2 of the color insert.) For many types of stars, the more carefully you look at the gaps, the more there are. Under high resolution—that is, high magnification both in the instrument and in your viewing or recording the result—the gaps look like narrow, dark lines crossing the spectrum. They are thus known as spectral lines.

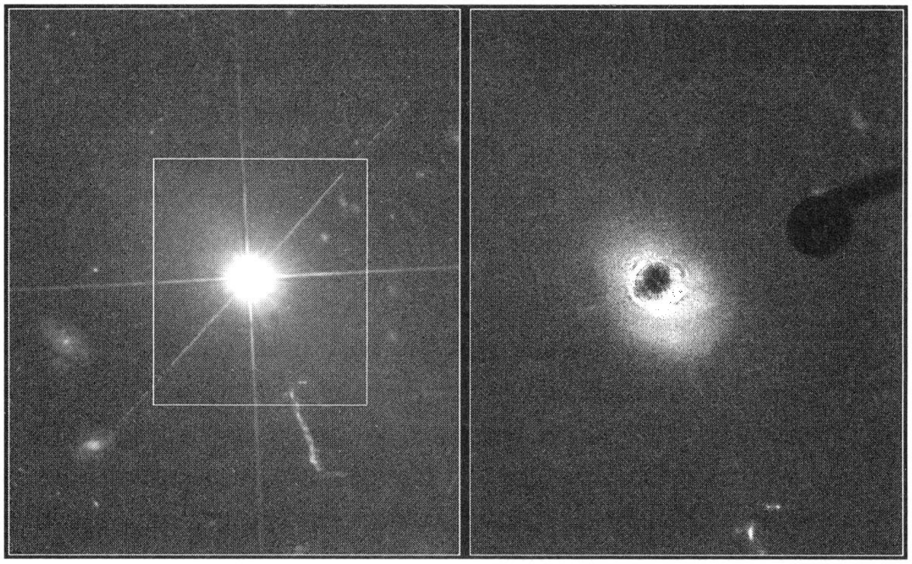
In the previous chapter, we saw how, in 1814, Joseph Fraunhofer mapped out the spectral lines from the Sun in detail for the first time. These Fraunhofer lines exist in all types of stars, though they often take on different intensities or patterns than the Fraunhofer lines on the Sun.

Spectra Reveal Stars' Secrets

One key to understanding the spectral lines is the set of lines from hydrogen. This set makes a distinctive pattern, with a line in the red, a second line in the blue, and more lines getting closer and closer as you look in the violet. Such a pattern is known by mathematicians as a converging series. Whenever you see such a set of spectral lines with this pattern, you know that you are seeing hydrogen gas. This set is known as the Balmer series.

Fun Sun Facts

Some decades ago, scientists using the largest telescopes discovered faint lines in some enigmatic pointlike objects in the sky. When a few of these lines became visible, their converging pattern conveyed that they were from hydrogen. They were shifted in wavelength because the source was so far away and, therefore, was moving rapidly in our expanding universe. If they are so far away, they must be exceptionally bright for us to see them. Only giant black holes with billions of times the mass of the Sun explain them. They are known as quasars.



Quasar 3C 273. It looks pretty much like an ordinary star, but the faint jet that extends from it makes it only quasi-stellar. The jet shows clearly in the left image, from the Hubble Space Telescope. On the right image, taken with Hubble's new "coronagraph" ability, the bright central part of the quasar was blocked out, revealing structure in the quasar's host galaxy.

(Left image: NASA and J. Bahcall [IAS]; right image: NASA, A. Martel [JHU], H. Ford [JHU], M. Clampin [STScI], G. Hartig [STScI], G. Illingworth [UCO/Lick Observatory], the ACS Science Team and ESA)

Another key to understanding the spectral lines is the set of lines from ionized calcium. Although there are thousands of times fewer calcium atoms than hydrogen atoms, most of the absorption done by these calcium atoms takes place in the visible. By contrast, most of the absorption done by hydrogen takes place in the ultraviolet at wavelengths too short to come through the Earth's atmosphere. The converging series of hydrogen lines that we see are merely a secondary, weaker set.

In Fraunhofer's notation, one of the lines of ionized calcium is almost exactly the same color as the fifth line in the visible series of hydrogen's Balmer series, a line known as H-epsilon. This line has Fraunhofer's notation of H. But the H-line is only one of a pair; the other line of the pair, close in color in the part of the ultraviolet on the edge of visibility, has been given the notation K. The H- and K-lines are about equally strong.

Using mainly the Balmer series and the H- and K-lines, you can classify the spectra of stars. If you look only at the position where either H or the fifth hydrogen line would be, you can't necessarily tell which you are seeing. But by looking nearby at the K-line, you can tell how strong the H-line would be. By looking at the rest of the Balmer series, you can tell how strong H-epsilon would be.

In the early years of the twentieth century, a team of computers—humans who computed—worked on the spectra of stars at the Harvard College Observatory. The most famous was Annie Jump Cannon, who classified the spectra of hundreds of thousands of stars. The stars with the strongest set of hydrogen lines were called type A, the ones with the next strongest set of hydrogen lines were called type B, and so on.

It later turned out that hydrogen lines were strongest at a certain temperature and weaker at both hotter and cooler temperatures than that. When the series of spectral types was rearranged to be in descending order of temperature rather than descending order of strength of hydrogen lines, the order came out OBAFGKM. They were then subdivided in tenths, so part of the list would be A8 A9 F0 F1 F2 ....

Our Sun is a type G2 star. That classification comes from the fact that its H- and K-lines are relatively strong, while it still shows moderate hydrogen lines. Many other hundreds of lines are detectable easily, and tens of thousands of lines are visible if you look very carefully.

The hottest stars are O stars, with surface temperatures of about 60,000 kelvins. The Sun has a surface temperature of about 5,800 kelvins. For a long time, the coolest stars known have been M stars, at about 4,000 kelvins. Work around the turn of the twenty-first century, especially in the infrared, where the black-body curves for even cooler stars peak (see Chapter 8 for a discussion of black bodies), has led to the need for more spectral classes. Cooler than M stars are spectral type L. (L was the closest letter to M that wasn't already in use or confusible with something else.) M and L stars have many molecules showing in their spectra, in addition to spectral lines from atoms. Only in very cool stars can molecules survive. Some of the L stars, and an even cooler spectral type called T, are a type of failed star called brown dwarfs. Brown dwarfs did not get quite hot enough for hydrogen fusion to begin. They may have some fusion of deuterium in them, though.

We often keep track of types of stars by the masses they have. The stars with the highest masses are the intrinsically brightest and hottest. O stars, in particular, have about 60 times the mass of the Sun. M stars, on the other hand, have only about $\frac{1}{100}$ the mass of the Sun.

The Sun is thus typical of stars, in that it is in the middle of the range of stellar brightness. It is also in the middle of the range of stellar mass; there are cooler stars and hotter stars.

However, the Sun isn't just average. There are many more cool stars than hot stars. Thus, there are many more stars cooler than the Sun than there are hotter stars. There are many more less massive stars than there are more massive ones. Though its properties are average, the Sun itself is in the hottest, brightest, most massive group of stars.

The Least You Need to Know

- The Sun formed from a collapsing, spinning cloud of gas and dust.
- The Sun is mostly hydrogen, has a substantial amount of helium, and contains traces of all the other elements.
- We find the abundances of the various elements in stars by studying their spectra.
- The spectra of stars tell us their temperatures.
- The Sun is midway between extremes of stars in mass, brightness, and temperature.