Chapter 13

Helium: Only on the Sun

In This Chapter

- Eclipses have been significant for thousands of years
- Helium, since found on Earth, was first detected in the Sun
- Coronium turned out to be highly ionized atoms, not a new element
- The magnetic field is important for shaping the corona
- The Sun is an excellent laboratory

The Sun tootles away year after year and century after century, converting hydrogen to helium and pumping out the energy to warm us on Earth. How can we re-create on Earth the conditions that we find in the Sun, to provide limitless power? What other lessons can we learn by studying the Sun, a celestial laboratory placed close enough for us to study in detail, but far enough away that it rarely harms us?

Historical Eclipses in Science, Literature, and Politics

Some of the most widely mocked astronomers were Hsi and Ho in ancient China, about 2000 B.C.E. They were said to have been so drunk that they failed to predict an eclipse. The emperor, supposedly, had their heads. The real story, though, is probably that Hsi-Ho was a name for a sun deity whose job included preventing eclipses. Did drunk astronomers really fail to predict the eclipse in 2134 B.C.E.? Probably not.

October 16, 1876 B.C.E.

Some of the oldest astronomical records are found in China on tortoise-shell chips. These "oracle bones" or "dragon's bones" sometimes have statements that may refer to eclipses. A Jet Propulsion Laboratory scientist and a UCLA professor of Chinese have used some of these oracle bones to date one eclipse to 1302 B.C.E.

Historical eclipses from long ago are particularly important because the Earth does not rotate at an absolutely constant rate. Sometimes it goes a tiny bit faster and sometimes a tiny bit slower, a result in part of how concentrated the Earth's mass is at various distances from its center. Changes in Antarctic ice, for example, can affect the speed of the Earth's rotation.

Eclipses are a sensitive way of measuring the speed of the Earth's rotation. We can use the Earth's current speed of rotation to predict where eclipse paths were hundreds or thousands of years ago. A total eclipse is such a spectacular phenomenon that clues to whether it occurred can sometimes be found in ancient records of various sorts. If the Earth's rotational speed has varied faster or slower than average, the observed eclipse path will have shifted east or west from the predicted path.

F. Richard Stephenson and his colleagues at the University of Durham in the United Kingdom have been leaders in interpreting ancient eclipses. They have found a slowing of the Earth's rotation over millennia. Since one Earth rotation is one day, they are basically measuring the length of the day. If the record of the 1876 B.C.E. eclipse is correct—which it might not be since it was found in a book from the sixth century B.C.E., over 1,000 years later—it would indicate that a terrestrial day was 0.07 second shorter in 1876 B.C.E. than today.

June 5, 1302 B.C.E.

How would you interpret "Three flames at the sun, and big stars were seen"? A team studying historic eclipses found this statement on "dragon's bones." The description could match the total eclipse of June 5, 1302 B.C.E., with the "flames" corresponding to coronal streamers.

585 B.C.E.

Herodotus, a Greek whose history has greatly shaped our views of ancient times, described in 430 B.C.E. how the total eclipse of May 28, 585 B.C.E., was visible during a war between the Lydians and the Medes. Herodotus wrote that the Lydians and the Medes ended the war as a result of the eclipse. What is more questionable in this report about 150 years after the fact was the statement that the Greek scientist Thales of Miletus had predicted the eclipse. From his careful study of ancient eclipses, Stephenson thinks that this time scale was too early and that, from what we know about the evolution of scientific abilities, there is no way that Thales could have predicted an eclipse that early. In our current evaluation, therefore, the story seems to be myth.

Lunar Eclipse of February 29, 1504

Christopher Columbus used this eclipse when he was stranded in Jamaica. Though it was merely a lunar eclipse, the story was picked up and associated later with solar eclipses, so we include it here. Columbus and his crew were suffering for lack of supplies. Fortunately, Columbus had a table of astronomical events and positions with him. It showed that there would be a lunar eclipse on February 29, 1504. He arranged to meet with the local chiefs during the eclipse and said he would take the Moon away. When they were sufficiently awed and scared, they arranged for food to again be brought to his crew.

April 22, 1715

Edmond Halley predicted the path of this eclipse, which passed over England from southwest to northeast. Ten years earlier, he had analyzed the paths of several comets in the sky and deduced that some of them represented the same comet returning. We still call that comet Halley's comet. Halley had sponsored Newton in producing his major work and in deriving the law of gravity. Halley continued to use the newfangled law of gravity for his predictions.

The map drawn for Halley of the 1715 eclipse was the first of its type, though maps are now routinely drawn to show the paths of eclipses over the Earth's surface. Space satellites now even peer down, showing the umbra moving across the Earth's surface.

After the 1715 eclipse occurred, a corrected map was issued, including the predicted path for the 1724 eclipse that would also pass over England.

Along with his map of the actual path of the 1715 eclipse, Halley added predictions for the path of the 1724 eclipse, shown here.

(Jay M. Pasachoff)

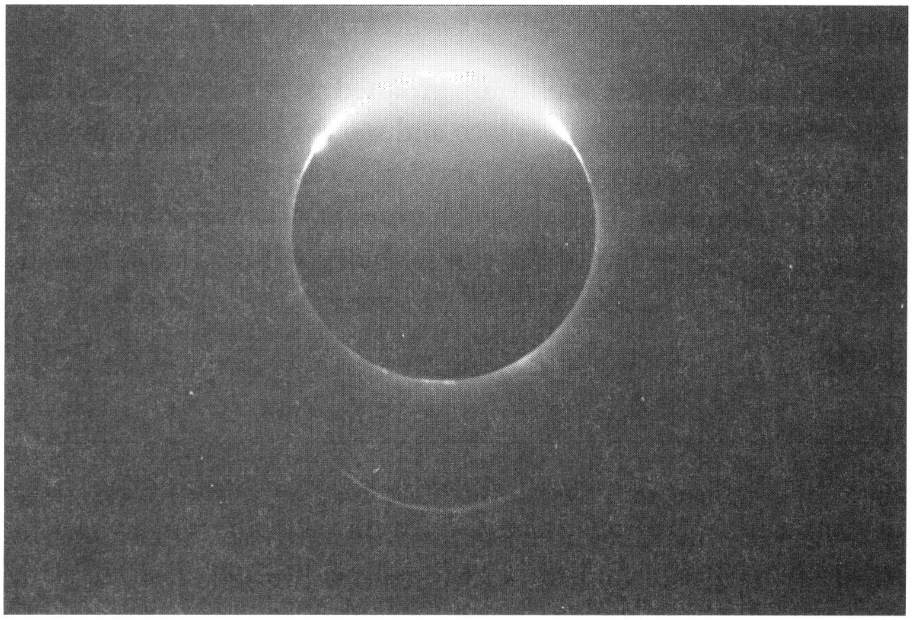
October 27, 1780

An eclipse was predicted for North America, but the problem for Harvard astronomer Samuel Williams was that the prediction was across enemy lines. The enemy, of course, was the British. Nonetheless, Williams set out for Penobscot Bay, in what is now Maine but was then Massachusetts, with a group of students and colleagues.

The delay of getting across the British lines turned out to be part of the problem, given also that there were errors on the maps they used. They wound up slightly outside totality. They did see the phenomenon that later was seen by Baily and named after him (Baily's beads).

May 15, 1836

English astronomer Francis Baily noted the beads of sunlight that appeared on the edge of the Moon during an annular eclipse that he observed from Scotland. He described them so well and so enthusiastically that we still talk at each eclipse of Baily's beads (though his name is misspelled as often as it is spelled correctly, it seems).



Baily's beads are very noticeable at the beginning and the end of totality.

(Williams College Expedition)

July 16, 1806

Tenskwatawa, a Shawnee prophet who was a leader of Native Americans in Ohio and Indiana about 200 years ago, acted as Columbus had. He threatened William Henry Harrison, who was then governor of the Indiana Territory and who later became president of the United States, to "blacken the face of the sun." When a large crowd watched Tenskwatawa at the eclipse, Harrison lost his attempt to diminish Tenskwatawa's influence.

1879 with No Eclipse, and June 21, 528

In Mark Twain's nineteenth-century story, the hero of *A Connecticut Yankee in King Arthur's Court* awoke in ancient England and fortunately knew ...

> that the only eclipse of the sun in the first half of the sixth century occurred on the 21st of June, A.D. 528 ... and began at 3 minutes after 12-noon. I also knew that no total eclipse of the sun was due in what to *me* was the present year—i.e., 1879.

He also remembered ...

> how Columbus, or Cortez, or one of those people, played an eclipse as a saving trump ..., and I saw my chance .... "Go back and tell the king," our hero said, "that at that hour I will smother the whole world in the dead blackness of midnight; I will blot out the sun, and he shall never shine again; the fruits of the earth shall rot for lack of light and warmth, and the peoples of the earth shall famish and die, to the last man!"

Our narrator became a hero when …

> It got to be pitch-dark, at last, and the multitude groaned with horror to feel the cold uncanny night breezes fan through the place and see the stars come out and twinkle in the sky. At last the eclipse was total, and I was very glad of it …. I said, with the most awful solemnity: "Let the enchantment dissolve and pass harmlessly away!" When the silver rim of the sun pushed itself out, a moment or two later, the assemblage broke loose with a vast shout ….

1885

Another famous old story was *King Solomon's Mines*, by H. R. Haggard, from 1885. In it, the hero gains influence by threatening to "darken the sun to-morrow." But Haggard allowed an hour for totality, so he obviously had never seen one himself.

Only on the Sun

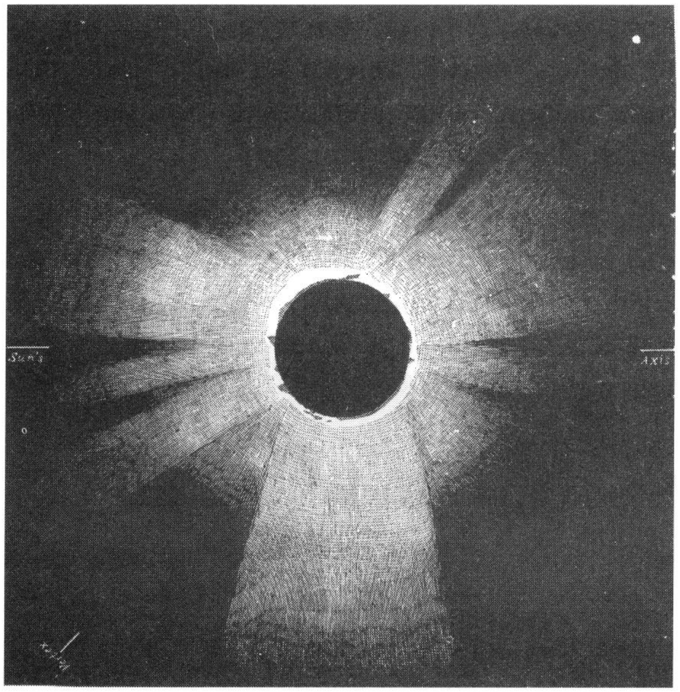
When Louis J. M. Daguerre invented photography in 1839, imaging the Moon was one of his prime goals. But it took until 1851 for the first astronomical photographs to be made successfully. The first photographs of the Sun were taken about then, including even an image showing the corona at the 1851 eclipse.

British amateur astronomer Warren De la Rue and Italian cleric Father Angelo Secchi took photographs of the 1860 eclipse from different locations. At that time, it was still debated whether the corona and other phenomena seen were on the Sun or in the Earth's atmosphere. From the fact that the prominences looked identical from different locations, scientists concluded that they were really on the Sun, since they were looking through different regions of the Earth's atmosphere.

Fun Sun Facts

Father Secchi wrote a wonderful book about the Sun. A NASA solar satellite to be launched into space will be named after him: Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI). It is to be a component of the Solar Terrestrial Relations Observatory (STEREO).

Scientific study of the sun was greatly enhanced in the nineteenth century by the discovery of spectroscopy. Newton had shown in the seventeenth century that white light from the Sun could be broken down into its component colors and that the colors could be reassembled to make white light again. But it took until the inventions and careful work of the German optician Joseph Fraunhofer in the early nineteenth century to transform spectroscopy into a useful tool for solar research.



An eclipse drawing of the eclipse of 1860, from a book by Father Secchi.

(Jay M. Pasachoff)

In Chapter 5, you learned that Fraunhofer spread out the spectrum of the solar photosphere in 1814. You learned how he labeled the strongest spectral lines with letters, especially C, D, and H.

The first time a *spectroscope* went to an eclipse was on the expedition to India in 1868 run by Pierre Jules César Janssen of Paris. Janssen could look only with his eyes at the spectrum; photography was not advanced enough to be able to record images of spectra during the brief interval of totality. The addition of a camera to record the spectrum transformed the spectroscope into a *spectrograph*, something that had already been accomplished by French scientist Léon Foucault.

Sun Words

A **spectroscope** is a device that you can look through to see the spectrum. A **spectrograph** is a device that records the spectrum on film or digital media.

Helium on the Sun

Janssen watched with amazement as the diamond-ring effect vanished and the chromosphere was briefly visible. He could see a bright yellow line in the spectrum at that time. He thought it was located at about the position of the D lines in the photospheric spectrum—a pair of lines, D_1 and D_2, that come from sodium.

Janssen realized that the yellow line was so bright that he could potentially study it even without the eclipse. Soon he opened the slit of his spectroscope and looked at the lines in a more leisurely manner. He discovered that the line, though yellow, was not exactly at the position of the D_1 and D_2 lines from sodium. He therefore called the line D_3. He said it was from "helium," since Helios is the Sun god in Greek mythology and it was an element found only on the Sun.

Coincidentally, at about the same time, Norman Lockyer in England, who hadn't been at the eclipse, decided to examine the Sun's edge with a spectroscope. He also discovered the D_3 line of helium. It took another 27 years, until 1895, for helium to be isolated on Earth. We now realize that it is element number 2 and makes up about 10 percent of all the atoms in the universe.

Coronium in the Corona?

Scientists took spectrographs to the eclipse in 1869. They realized that during totality, there was a bright green emission line in the spectrum. That showed them that hot gas was present in the corona, itself a major discovery. But they didn't know what the gas was. It was soon called coronium, since it was apparently (for the people of that time) found only in the corona. Charles Young, a Princeton professor and leading American expert on the Sun, wrote in his 1895 book on that topic, "As to the substance … we have no knowledge as yet, though the name 'coronium' has been provisionally assigned to it, and the recent probable identification of 'helium' in terrestrial minerals gives strong hope that before very long we may find coronium also."

Over the following years, other coronal emission lines were found. The second strongest in the visible occurs in the red and is known as the coronal red line, to go with the coronal green line.

The coronium problem proved much harder to crack than the helium problem. The key came from studies in the 1930s of novae, explosions on star surfaces. The spectra of two novae showed emission lines that the brilliant Swedish spectroscopist Bengt Edlén identified with unusual transitions in very hot iron atoms. Edlén went on in 1939 and the following years to show that the several coronium lines that had been observed since 1869 came from very hot versions of several elements, especially iron, calcium, and nickel. His studies started with cooler gases and extrapolated to the hotter ones that he couldn't study in the laboratory but that he showed existed on the Sun. So, the coronium problem took 70 years to solve. There was no such thing as "coronium," after all! However, many lines of evidence support Edlén's deduction that the solar corona is very hot and that "coronium" is explained by these hot gases of ordinary elements.

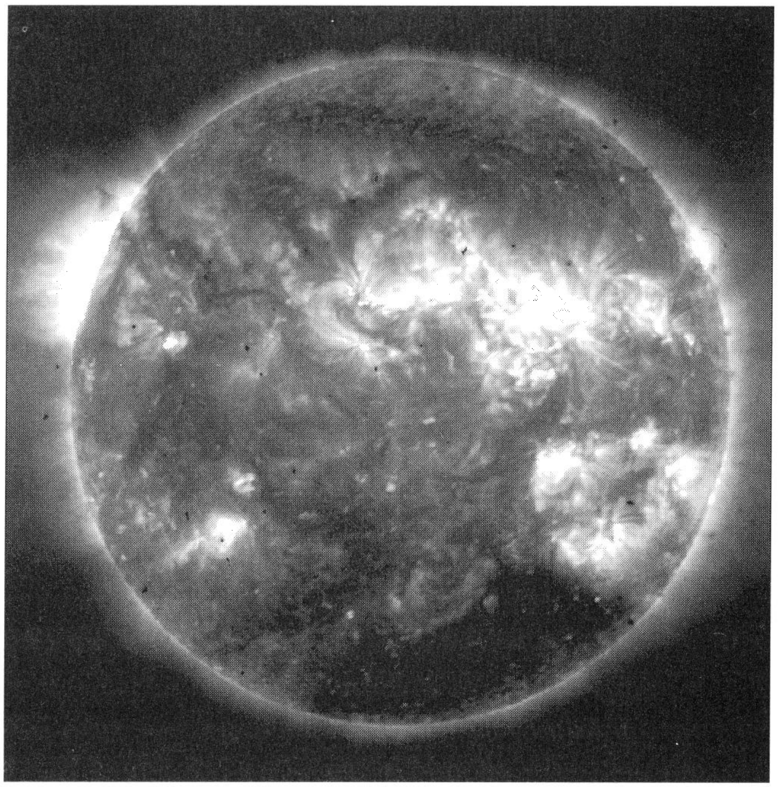
Solar Scribblings

When Leon Golub of the Harvard-Smithsonian Center for Astrophysics sent up a rocket for the eclipse in 2001 that observed nickel-17 (nickel that has lost 16 electrons out of its quota of 28), he was observing gas at a temperature of over 5 million°F (3 million°C).

Solar Scribblings

Other indications showed that the corona was very hot even before Edlén's spectroscopic and theoretical work. Aside from the emission lines, the inner corona doesn't show any absorption lines. Yet if the coronal gas were cool, it should reflect the absorption lines in the photospheric spectrum. The solution to that conundrum is to realize that the coronal electrons are moving very fast—that is, they have high temperature. From the smearing of the absorption lines, we can deduce that the coronal gas must be millions of degrees. But the experiment is very hard to do.

In particular, the coronal green line comes from iron that has lost 13 of its 26 electrons. The coronal red line comes from iron that has lost 9 of its 26 electrons. The hotter it is, the more electrons are given enough energy to separate from the atom.



An image of Ni XVII—that is, 16-times-ionized nickel—taken from a rocket flight.

(Leon Golub, SAO)

A Laboratory in the Sky

Often objects in the sky present us with new situations that we earthlings haven't experienced. We try to use those unusual objects and events to understand more about the universe in which we live.

Magneto-hydro-dynamics

When we look at the corona at an eclipse, we see streamers extending into space. Some are called helmet streamers, in which the base is wider and the top is pointy, like an old Prussian helmet that we might see in the history books or in a movie. These streamers are held in place by the Sun's magnetic field.

When we look close to the limb of the Sun, we see loops of gas in the corona. These coronal loops are also held in place by the Sun's magnetic field. The TRACE spacecraft makes particularly detailed images of them.

These magnetic formations mimic lines of magnetic force traced by iron filings held near a magnet. Some scientists have calculated the magnetic field at a theoretical surface arbitrarily placed near but above that of the Sun, and have shown how the magnetic field extends into space. They have even predicted what the corona will look like during an eclipse, though the predictions have not been entirely successful.

On Earth, we are looking for ways of generating power for business and home use. We mainly now use fossil fuels, which lead to greenhouse warming (which we will discuss later) and to dependence on oil from the Middle East and other politically undesirable places around the world. Nuclear power is free of the consequences of global warming, so it would be desirable from that point of view if it could be even more widespread than the approximately 20 percent of energy it now generates in various countries. But concerns about weapons proliferation, the economics of the nuclear cycle, and long-term hazards of nuclear waste have left the nuclear industry in a moribund state.

Solar Scribblings

The shape of the magnetic field calculated for the corona sticks out like a ball with spiky hair sticking out to outline the coronal streamers. These calculations are therefore known as hairy-ball models.

The Holy Grail of power has for a while been nuclear fusion, the same process that fuels the Sun and stars rather than the nuclear fission that makes today's nuclear power plants work. One of the major problems with fusion is that it works by putting together two nuclei; each nucleus has a positive charge. The nuclei thus repel each other, and they have to be forced close enough to fuse. That requires high temperatures—millions of degrees—and sufficiently high densities. Where do we find such conditions in nature? Of course, in the Sun and stars.

As we mentioned in Chapter 1, the fusion reactor at the Sun's core is 93 million miles away from us and is held in place by gravity at a safe distance from us. Other million-degree gas at the Sun is in the corona, where it is held in place by magnetic fields. For fusion to take off on Earth, we must control the fusion process and keep hot, dense gas in place. No actual container can hold such hot, dense gas. The main ideas for overcoming the obstacle involve a device called a tokamak, which uses magnetic fields to make a "magnetic bottle" to hold in the gas. Unfortunately, the magnetic bottles are not stable, and they come apart in a fraction of a second. By studying the laws of physics through observation of hot gases held in magnetic fields in the Sun, we may learn more about how to control fusion on Earth.

The Solar Scoop

Tokamak is a Russian acronym for "toroidal magnetic chamber with an axial magnetic field." That is, a tokamak is a bagel-shaped (doughnut-shaped) holder (thus, a toroidal holder) with a magnetic field centered on the toroid's axis—the line perpendicular to the plane of the bagel and at the center of its central hole. The next-generation tokamak is to be ITER, the International Thermonuclear Experimental Reactor, a $5 billion project.

Fun Sun Facts

In the Sun, a nucleus of ordinary hydrogen fuses with other hydrogen nuclei to build up to helium, which incorporates four hydrogens. At still lower temperatures, deuterium fuses to make helium. Ordinary hydrogen is just a single proton, while deuterium—also known as "heavy hydrogen"—is a proton and a neutron bound together. Types of failed stars called brown dwarfs have recently been discovered by the dozen. They don't have enough mass to get hot enough inside to fuse ordinary hydrogen, but they do fuse deuterium.

Gas that is ionized—that is, separated into its positive particles (nuclei) and negative particles (electrons)—is known as plasma, as we described in Chapter 6. The Sun and stars are made of plasma. The study of things moving is called dynamics, and the study of the motion of fluids (and other things that flow, including gases) has long been called hydro- from the study of moving water. When you add the term magneto- for the magnetic field, you get magneto-hydro-dynamics, or *magnetohydrodynamics*, often simply called *MHD*. The laws of MHD govern the hot, ionized gas in the Sun.

Sun Words

Magnetohydrodynamics, or **MHD,** is the study of the motion of ionized gases (plasmas) in magnetic fields.

Forbidden Lines

Spectral lines—whether emission lines or absorption lines—come from electrons changing orbits in atoms. For each orbit, we say that each electron is on a certain "energy level" and that the energy levels are spaced out in certain ways rather than being continuous. In 1913, Niels Bohr worked out the basic idea: Each electron stays on a certain energy level and can jump to another energy level, but it cannot take intermediate values or energy. The situation is similar to climbing stairs: You can be on one step or another, but you cannot hover between them. Whenever an electron changes from one energy level to another, the difference in energy corresponds to a spectral line of a corresponding color.

When the laws of quantum mechanics were worked out in detail in the late 1920s, some rules turned up that governed which pairs of energy levels could give off and take up an electron in a given jump. These rules showed a certain set of jumps that are *permitted.* These permitted jumps corresponded to *permitted lines.* All other transitions were called *forbidden.*

Sun Words

Permitted lines are spectral lines that are common (we say "allowed") from transitions between two energy levels of atoms. **Forbidden lines** are spectral lines that would occur so rarely that other circumstances in atoms, like collisions, would keep them from occurring. Thus, they appear only in gas of extremely low density.

Fun Sun Facts

The solar corona has only about a billion particles in each cubic centimeter of gas. The Earth's atmosphere has trillions of times more particles in each cubic centimeter. The density of the solar corona is lower than we can make in laboratories on Earth.

But forbidden lines are not absolutely impossible; they are merely of low probability. If an atom is sitting on one energy level, it spontaneously can drop to a lower energy level, just as a ball rolling off a top step can fall to a bottom one. But if the ball has a low probability of rolling off the step, someone might kick it off first, and it wouldn't necessarily go to the lower step it would have fallen to. (It could go to a higher level or even out of the atom entirely.) The same thing happens on the Sun and on stars. On the Sun as well as on the Earth, jumps that correspond to permitted lines happen often enough per set of atoms that the electrons can spontaneously fall to lower energy levels. But forbidden lines can't be seen in ordinary circumstances on Earth because the density of terrestrial gas is high enough that the electrons are knocked out of the higher energy levels before they fall to the lower levels, thus preventing the transitions that give off these lines. In the corona of the Sun, however, the density is so low that the electrons can sit around on their upper energy levels long enough for them to spontaneously drop down, emitting forbidden lines.

The coronal emission lines that appear in the visible part of the spectrum, such as the red and green coronal lines, are all forbidden lines. These highly ionized species of atoms such as iron have permitted lines, too. But these permitted lines occur at very short wavelengths, too short to see in the visible. They occur in the far ultraviolet and x-ray regions, and can be studied from spacecraft.

Solar Scribblings

When a rocket went up to study the far ultraviolet solar spectrum during the eclipse of 1970, it got more than scientists expected. Not only did they find the permitted lines of iron and other elements that they expected, but they also found even stronger emission from neutral hydrogen. But the solar corona was millions of degrees, too hot for hydrogen to remain neutral. It turned out that even at those high temperatures, just a little bit of neutral hydrogen remained unionized, and that small amount was enough to scatter sunlight toward Earth to provide the observed emission. Later spacecraft were designed to make direct studies of this emission, known as Lyman-alpha, directly, to map the temperature of the corona.

Solar Neutrinos

In Chapter 3, we discussed the solar neutrino problem and its solution in terms of neutrinos changing from one type to others. The history of the solar neutrino problem is another illustration of the usefulness of the Sun as a laboratory in space.

The neutrinos from the Sun have been monitored for about 35 years. Only in 2002 did a neutrino detector in the same Japanese mine record neutrinos emitted by power plants all over Japan. The work was used to verify that neutrinos indeed change in "flavor" after their formation.

Solar Scribblings

Trillions of solar neutrinos pass through you each second. They interact so rarely with matter that they are hard to pick up even when you are trying. Just to scare people away from our equipment at the eclipse in Australia in 2002, we hung a sign saying "Caution: Solar Neutrinos."

Solar Scribblings

When the neutrino problem first emerged in the 1960s, physicists were scornful of astronomers analyzing it. The physicists said that the astronomers just didn't understand the Sun well enough, and that they must have the temperatures in the middle of the Sun wrong. The astronomers said, in return, that they knew about the Sun and that the physicists had their basic physics of neutrinos wrong. I am glad to report that the astronomers have been vindicated and that "new physics" beyond the "standard model" of elementary particles must exist to allow neutrinos to change in "flavor." No doubt the importance of the result led to the Nobel Prize committee for Physics deciding to award half the prize for this topic.

The Least You Need to Know

- The positions of eclipses from thousands of years ago can tell us how the day has changed in length.
- Each total eclipse has its own particular story.
- The fundamental element helium is only one of many things found by studying the Sun.
- Studying the Sun helps us understand laws governing the motion of hot gas in magnetic fields.
- Only in low-density gas like the corona can we observe the forbidden lines in the spectra of elements.
- Studying the Sun can teach us basic laws of physics.