Chapter 2

The Active Sun

In This Chapter

- Sunspots look dark only because they are surrounded by brighter stuff
- Sunspots are cooler than the surrounding stuff
- Sunspots show where the Sun's magnetic field is strongest
- Sunspots vary with a cycle about 11 years long
- Many other things on the Sun also vary with the same cycle as the sunspots

Although you should never stare at the Sun, over thousands of years there have occasionally been times when there is just the right amount of haze in the Earth's atmosphere that the Sun hasn't appeared too bright. Sunspots were discovered at such times even before they were first seen with telescopes in 1610, by Galileo and others.

Anyway, on the surface of the Sun—now studied with special filters or with electronic cameras—dark spots appear. These spots appear tiny on the surface, although they are really often larger than Earth. They have long been known as sunspots, a name applied in the time of Galileo about 400 years ago.

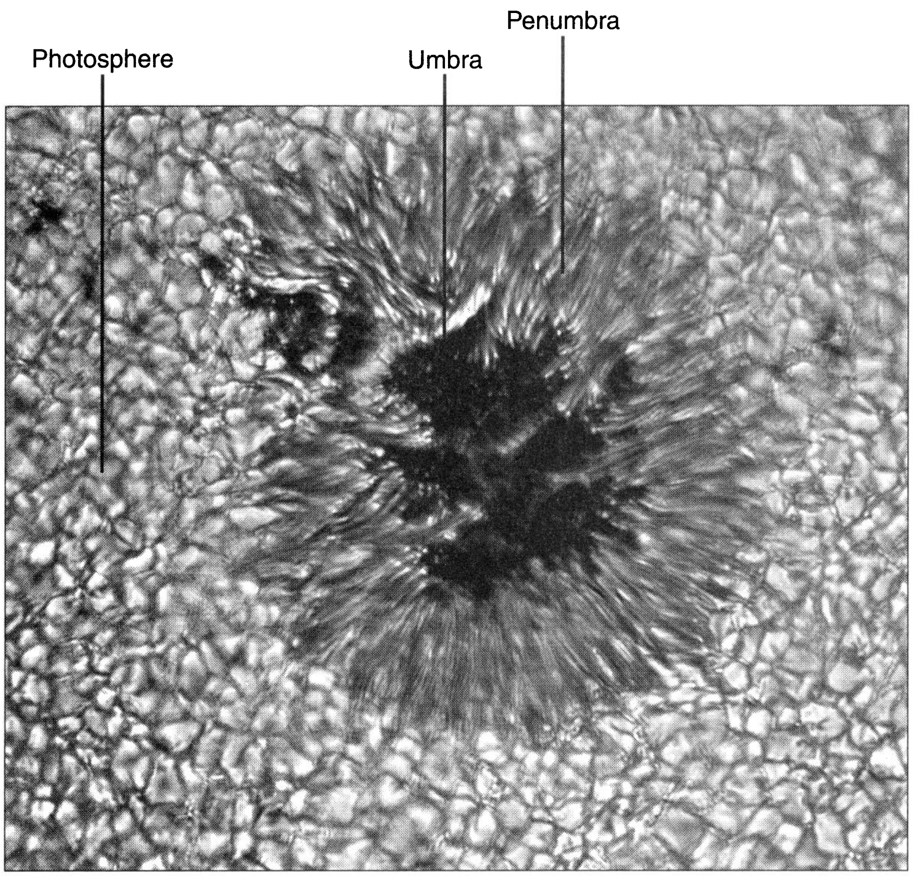
For about 150 years, we have known that the number of sunspots on the Sun increases and decreases—we say that they wax and wane—with a period of about 11 years. That period is known as the *sunspot cycle.* When we are at the minimum of the sunspot cycle—called sunspot minimum—no spots may be visible on the Sun for days at a time. But when we are at the maximum of the sunspot cycle—called "sunspot maximum"—a hundred or more sunspots could be visible at a time. And of course, there are probably just as many sunspots hiding on the Sun's far side.

Sun Words

The **sunspot cycle** is the 11-year up-and-down in the number of sunspots.

Dark Spots Are Really Bright

Photos of sunspots show that they have dark centers that are surrounded by alternating bits of light and dark material. The darkest part of a sunspot is its umbra, named from the Latin word for "shadow." The somewhat lighter region around it is its penumbra, named from the Latin words for "almost shadow."



A sunspot has a dark center known as the umbra, and lighter surrounding parts that are known as the penumbra.

(T. Rimmele/NSO/AURA/NSF)

Sunspots come in a variety of sizes, but even ordinary ones on the Sun are much larger than the Earth. If you could somehow take one of those sunspots off the Sun and hold it out in space all by itself, it would shine as brightly as the full Moon. It merely *looks* dark because it is surrounded by even brighter gas.

Sunspots are about 2,000 kelvins cooler than the photosphere that surrounds them. So they are about 4,000 kelvins instead of about 6,000 kelvins. But that makes them a lot dimmer because the amount of energy that anything gives off goes down with the temperature raised to the fourth power. So although the temperature in the photosphere is $6{,}000 \div 4{,}000 = 6 \div 4 = 1.5$ times hotter, it is $(6{,}000 \div 4{,}000)^4 = 1.5^4 = 1.5^2 \times 1.5^2 = 2.25 \times 2.25 = 5$ times brighter. (We won't do anything in this book that requires a calculator. We'll use only math that you can do in your head. That will be accurate enough for us.)

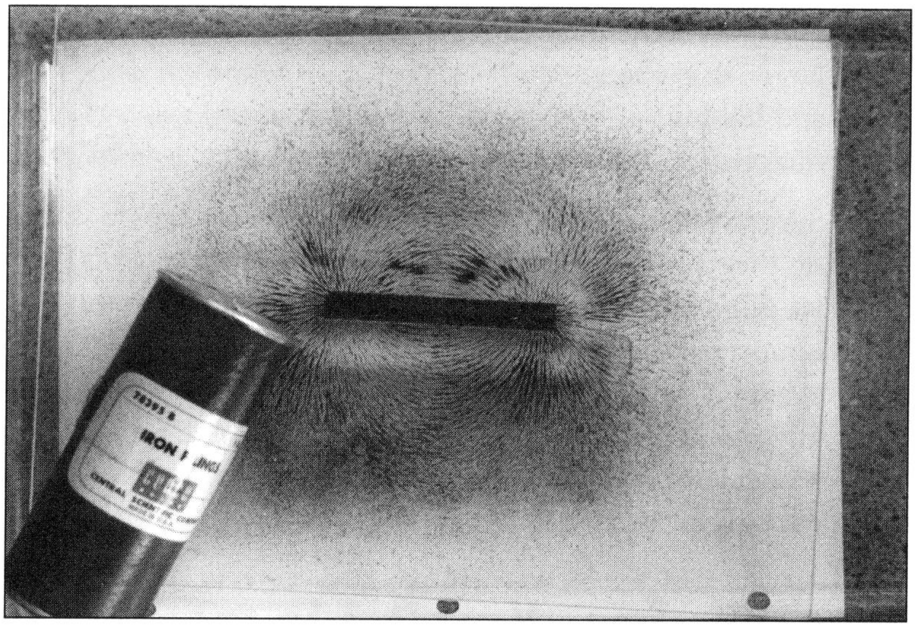
Magnets: From Your Refrigerator to Your Sun

What's a magnet? It is something that pulls certain materials toward it or pushes them away. It uses magnetism, which is one of the basic forces of nature. Scientists have known for more than a hundred years that magnetism and electricity are kindred forces, different aspects of a unified force known as electromagnetism. We use electricity and magnetism on Earth every day—every motor in your house or your car relies on both, for example.

Magnets attract only certain materials or materials in certain conditions. Iron, for example, is attracted to magnets. Just hold a magnet up to an iron nail. The nail will even jump across a bit of air to get to the magnet, if the magnet is strong enough.

To see what the attraction by a magnet looks like, get some iron filings. I used to think that they were something special, but you can really get them (unless you want to write away to, or order on the Internet from, a scientific supply company) merely by filing away a nail with a regular file. Put the magnet under a piece of paper and drop the filings on top of the paper. Sometimes tapping the paper lightly with your finger helps the iron filings find their way to overcoming friction that holds them to the paper.

You will see a pattern of lines on the page. These are "magnetic lines of force." They go from one part of the magnet, called a north pole, to another part of the magnet, called a south pole. Some complicated magnets may have more than two poles, but never do we find only one pole. You never find just a north pole or just a south pole.



Magnetic lines of force around a bar magnet, produced by dropping iron filings on a piece of paper that is placed over the magnet.

(Jay M. Pasachoff)

On the Sun, moving hot gas sets up *magnetic fields.* In particular, in sunspots, a very strong magnetic field appears. That magnetic field holds gas in place, since the gas can move only along the direction of the magnetic field lines and not across them. In this way, the magnetic field acts as a giant hand, tamping down motions. It cools the gas. And when the gas is cooler, it is darker.

Sun Words

A **magnetic field** shows the direction and strength of magnetism.

We can actually see the shape of magnetic field lines on the Sun, as we could see the lines from a refrigerator magnet if we used it to attract iron filings. A wonderful NASA spacecraft called Transition Region and Coronal Explorer (TRACE) can see detail on the Sun so fine that the magnetic lines of force show. We are actually seeing the glowing gas that is following along the shapes of the magnetic lines of force.

Fun Sun Facts

You need a special filter or a special telescope to look at spots on the Sun. A little telescope device called a Sunspotter is available for about $300. It folds—bounces—the incoming beam of sunlight back and forth so that the device is only about 18 inches high. You can point it toward the Sun to give you a sunspot image projected on a piece of paper. Setup time is only about 10 seconds. See www.starlab.com/ltiss.html.

How strong is the magnetic field in a sunspot? The overall, average magnetic field on the Sun's surface is about 1 gauss, and the magnetic field of a toy magnet is about 100 gauss. But in a sunspot, the magnetic field is 3,000 gauss, much higher. This high magnetic field keeps the sunspots cool and, therefore, dark. (In the international system of units now in scientific use, tesla, which are 10,000 times larger than gauss, are mandated. Since these units are named after people, their symbols are capital letters—T and G, respectively. So perhaps we should be saying that a sunspot, which we said was 3,000 G, is 0.3 T, whereas an ordinary toy magnet is about $\frac{1}{10,000}$ T. Note that the symbols are capital letters, though the units gauss and tesla are written with lowercase letters, because both Gauss and Tesla were people.)

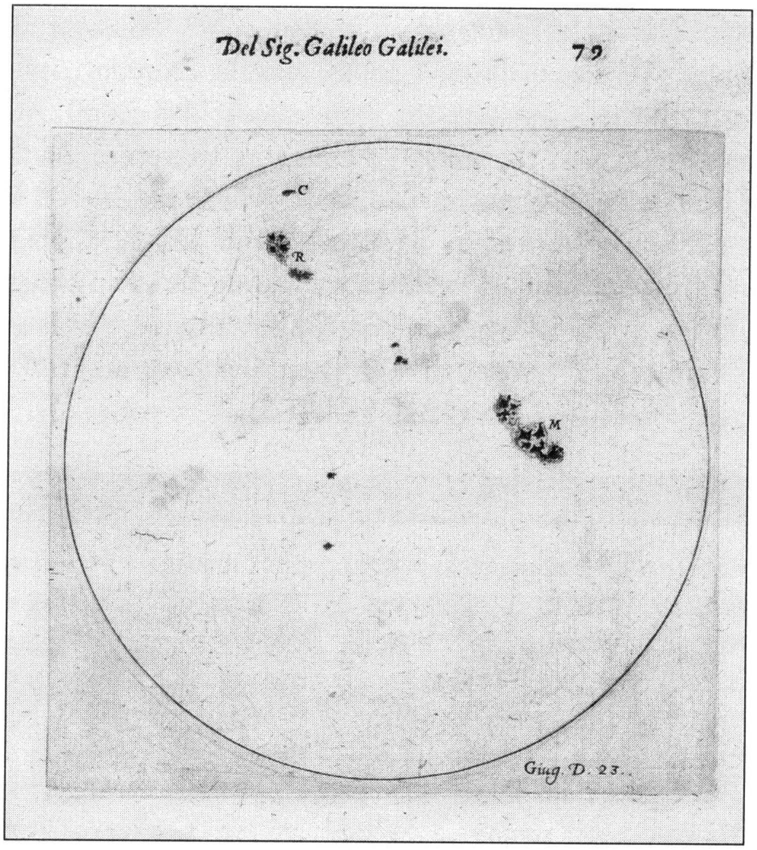
Fun Sun Facts

You can use binoculars or a telescope to project an image of the Sun onto a piece of paper or cardboard or even onto the ground. But you must be very careful not to look up through the optical device at the Sun. If you are using binoculars, extended use could cook the optics inside. In any case, block off the big end of half of the binoculars with cardboard carefully taped on with heavy tape. Then hold the device (telescope or binoculars) about 18 inches in front of the cardboard, with the big end of the binoculars toward the Sun. *Remember: Don't look through the binoculars at the Sun.* Instead, use the binoculars to project the solar image onto a piece of paper. Focus or move the device toward and away from the Sun until you see a sharp solar image. Don't stare at the image for more than a few seconds at a time, since it will be very bright even though it is merely a projection.

Sunspot Cycle

When Galileo discovered sunspots, some of his contemporaries found them, too. In fact, priority for discovering sunspots was part of Galileo's fight that led to his house arrest. Anyway, finding a sunspot was a big thing in the seventeenth century. It often led to publication of a scientific paper, with the *Philosophical Transactions of the Royal Society* of London as a prestigious source. (It is fun that *Phil Trans* is now available online back to volume 1 in 1665, albeit by subscription.)

It wasn't until the mid-nineteenth century, about 150 years ago, that an amateur astronomer noticed that there were actually sometimes a lot of sunspots on the Sun and that the number of sunspots rose and fell with a detectable period. The peaks of the numbers of sunspots occurred about every 11 years, and the times when there were almost no sunspots also differed by about 11 years. The period isn't a constant 11 years—sometimes the interval is only about 8 years, and sometimes it is 12 years or more, but 11 years has proved to be a good average.



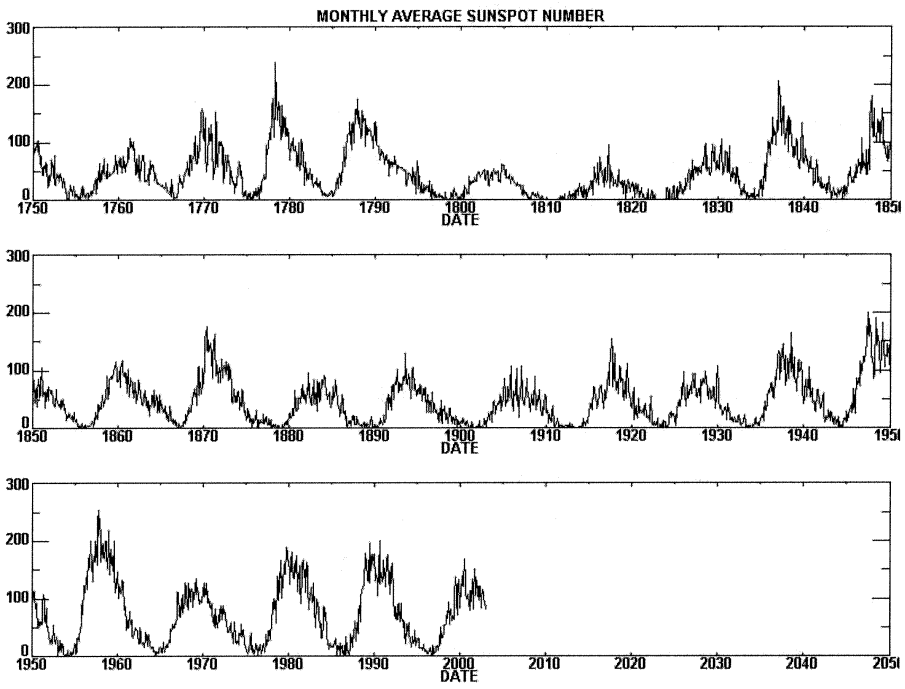
The Sun, with sunspots, from a book by Galileo in 1613.

(Jay M. Pasachoff)

This 11-year period is known as the *sunspot cycle*. It isn't one of those minor effects that scientists sometimes find in which you have to use careful or statistical methods to tease a scientific conclusion out of messy data. No, the sunspot cycle just knocks your eyes out.

For historical reasons, we usually plot not the actual number of sunspots on the Sun, but rather the "sunspot number." This value, also called the Wolf sunspot number, after its nineteenth-century inventor, takes note of the fact that sunspots don't usually appear in isolation on the Sun. Rather, they appear in groups. The sunspot number gives 10 times more importance to groups than it does to individual spots.

Let's say there are four sunspots on the Sun. If they could be scattered around the Sun evenly (this could never happen for magnetic reasons, as we shall soon discuss), there would be four groups, each containing one spot. Thus, the sunspot number would be 44: 4 groups × 10, plus 4 spots. If, as is more likely, there were two regions each with two spots, the sunspot number would be 24: 2 groups × 10, plus 4 spots. And if the four spots were in the same group, the sunspot number would be 14. Still, when the sunspot number is high, there are a lot of sunspots, and also a lot of groups of sunspots, on the Sun.



The sunspot cycle.

(NASA's Marshall Space Flight Center)

Some peaks of the sunspot cycle are higher than other peaks. We don't know why. Some say that there is a longer cycle that is superimposed on the shorter cycle. But there is no proof of that. In fact, a couple of years before the most recent sunspot maximum in 2001–2002, there was a session at a scientific meeting at which three papers were given. The first said that the peak would be higher than average, the second said that the peak would be lower than average, and the third said that the peak would be average. (It wound up about average, though lower than the two previous peaks.)

The Spinning Sun

One of my friends was making an IMAX movie about the Sun—and you should see it in an IMAX theater, if you can, or buy the videotape or DVD, if you can't. The movie, called *SolarMax*, contains fabulous footage taken with telescopes on the ground and in space. But my favorite part of the movie is the set of images taken from a book I own: *Macchie Solare* (that is, *Sunspots*), written by Galileo and published in Rome in 1613. My friend aligned and animated a series of photos of full-page drawings that Galileo had published. The movie shows the sunspots moving as the Sun rotates. (My name was only slightly misspelled in the movie's credits.)

So the Sun rotates on its axis—that is, spins—about once a month. Actually, the Sun isn't a solid body like Earth, so all of it doesn't have to rotate in the same amount of time. And that is what happens. Things on the Sun's equator rotate in about 25 days, while things halfway north or south rotate about 2 days a month slower. Things near the pole take more than 28 days to go around. Two and a half days out of 25 is about 10 percent, which may seem like a slight difference. But for every 10 rotations of the equator, sunspots at higher latitudes go around 1 time fewer. (This differential motion also occurs as you go deeper into the Sun.) So if you were to start with a magnetic line of force stretched from pole to pole, the equatorial part of it would gradually but inexorably go faster around, and would eventually lap the higher latitudes. After some years, it would go around a few extra times. The lines of force get wound up in this way.

Now find a rubber band. Hold one part in your left hand and the opposite part in your right hand. Then twist your hands in opposite directions. You will see the rubber band start to kink, and a piece will push up higher. This is the same effect that makes sunspots. Magnetic lines of force at or under the Sun's surface kink as a result of the Sun's equator rotating faster than its poles. When a kink in the magnetic lines of force pushes up through the surface, we see one polarity where it pierces the surface from below and the opposite polarity when it goes back down.

This rotation of the Sun that is different at different latitudes is called differential rotation.

Leading and Trailing

Looking at a map of solar magnetism, you may not notice a particular effect at first. But after a while, it hits you: The black regions are to the right of the white regions in the top hemisphere, while they are to the left in the bottom hemisphere. Because the Sun is rotating with the side facing us going from left to right, we say that the sunspot in the direction of rotation is "leading" and the behind sunspot is "trailing."

Sunspots always appear in groups that contain both polarities. That is because magnetic lines of force always have to start on one polarity and end on the opposite polarity. Thus, though the lines of force don't show on this overhead view, they extend from the bright regions to the nearby dark regions. Sometimes bright and dark are well separated, while other times they are jumbled. We will see later on that the jumbling can lead to explosions known as solar flares.

Solar Scribblings

The magnetic field of sunspots was studied and mapped out about 100 years ago by George Ellery Hale. Hale started as a solar scientist but went on to be the greatest telescope builder for astronomy in general, with his work on the 100-inch telescope on Mount Wilson and the 200-inch telescope on Palomar Mountain.

Notice also that in the northern hemisphere, white polarity leads black. But in the southern hemisphere, it is the other way around. Which polarity leads is always different between the two hemispheres. This effect is known as Hale's Polarity Law, after George Ellery Hale. After each 11-year cycle, the polarity that leads switches in each hemisphere. Thus for 11 years, white (north, say), polarity leads in the northern hemisphere, and then black polarity leads for the next 11 years. As a result, the real sunspot cycle is 22 years long. Only then are the polarities back the way they were before.

Fun Sun Facts

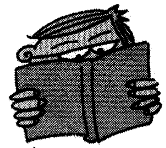
How do astronomers measure magnetism on the Sun, which is 93 million miles away? They use an effect discovered 100 years ago by the Dutch scientist Pieter Zeeman. This Zeeman effect causes a difference in some special parts of the Sun's spectrum, which we will be discussing later. This difference depends on how strong the magnetic field is. Using the Zeeman effect, scientists make maps of the magnetism over the whole Sun. The image shows one polarity as dark and the other as bright. (Astronomers don't always even note which is north and which is south; only the fact that they are opposite counts.)

Activity Is General and Goes in Cycles

The sunspot cycle was historically the first cycle to be found on the Sun. But now we know that a whole host of things on the Sun vary with the same period. All these things result from the Sun's magnetic field. We say that rather than just a sunspot cycle, we have a *solar-activity cycle.*

If you use a special kind of solar filter that passes radiation only from hydrogen, the regions around sunspots are brighter than average. They have long been given the name plage (pronounced *plahje*, after the French word for "beach"). This kind of filter costs $500 or more each—and, of course, professional ones cost a lot more than that. Anyway, following the plages shows not only the Sun's rotation, but also, over years, the solar-activity cycle.

If you can get above Earth's atmosphere, which we can with spacecraft, you can study parts of the radiation from the Sun that doesn't come through Earth's atmosphere.



Sun Words

The **solar-activity cycle** is the sunspot cycle matched in other solar phenomena.

The Spectrum

Our eyes are tuned to what we call visible light, which extends from red through orange to yellow, to green, to blue, to indigo, and to violet. However, in 1800, the astronomer Williams Herschel discovered the *infrared.*

Infrared is a kind of electromagnetic radiation, like light. It works just like light, but infrared waves are more stretched out than light waves. We say that it has longer wavelengths. At still longer wavelengths, we reach radio waves.

Going the other way from the solar spectrum, we go beyond the violet end to get ultraviolet light, which has shorter wavelengths than violet, which in turn, has shorter wavelengths than blue. At still shorter wavelengths, we get extreme ultraviolet (XUV or EUV to astronomers). And at even shorter wavelengths, we get first x-rays and then gamma rays. Much of these radiations don't come through the Earth's atmosphere. In particular, gamma rays, x-rays, and ultraviolet are blocked. Most of the infrared is blocked. But visible light, some of the infrared wavelengths, and radio waves pass right through the Earth's atmosphere, and we can study them on the ground.

Fun Sun Facts

Think of the friendly fellow ROY G. BIV, the initials of the color names, to remember the colors. In 1800, the astronomer William Herschel (who had earlier discovered the planet Uranus) put a thermometer beyond the red on a spectrum. The temperature went up. Herschel had discovered *infrared* (that is, beyond the red, from the Latin prefix *infra-*).

Sun Words

X-rays are like light, only hundreds or thousands of times shorter in wavelength.

Starting in the late 1940s, using captured V-2 rockets, *x-ray* telescopes have been launched above the atmosphere to study the Sun. (One of the pioneers in this work shared in the 2002 Nobel Prize in physics.) Once x-ray telescopes got advanced enough to see details on the Sun, scientists learned that the regions around sunspots are bright in x-rays. The number and position of these regions varies with the solar-activity cycle. Current satellites aloft, like the SOHO and TRACE, make images in the extreme ultraviolet. These images, too, show bright regions of solar activity. The number and brightness of these images wax and wane with the solar-activity cycle.

When the magnetic field gets all twisted up in active regions, energy is stored up. Sometimes something triggers an explosion, which releases all the stored energy in seconds. The result is a *solar flare.* Solar flares eject matter at high speed as well as emitting x-rays and *gamma rays,* all of which reach Earth in minutes to days. They are a major source of space weather. The number and strength of solar flares is a major indicator of the solar-activity cycle. We have the strongest flares and the greatest number of them near the peak of the solar-activity cycle, and few flares—and weak ones, at that—at the solar-activity minimum.

Sun Words

A **solar flare** is a powerful, sudden eruption on the Sun. **Gamma rays** are like light but have even shorter wavelengths than x-rays.

A much less explosive phenomenon is also often seen at the edge of the Sun. These are *prominences.* They glow especially reddish, like the chromosphere, and can also be seen at solar eclipses. Even without eclipses, special telescopes can follow the chromosphere and prominences. Sometimes prominences are seen to erupt, though they do so over hours instead of the seconds of flares. Very often, you will see a picture in the newspaper or on the web labeled "flare," while it was really a prominence. Anyway, prominences also follow the solar-activity cycle.

Sun Words

Prominences are structures held in space above the Sun by the Sun's magnetic field and seen when they are on the edge of the Sun. **Filaments** are what prominences look like when you see them from above.

When you look right at the disk of the Sun rather than at its edge, using hydrogen light that shows prominences well at the Sun's edge, you see dark streaks curving across the surface across plages and between sunspots. These are *filaments,* prominences seen from above. Though prominences look bright because we are seeing them projected against the dark sky, filaments look dark because we are seeing them projected against the bright solar surface. Sometimes when a flare erupts halfway across the Sun, a few minutes later you see a filament wink off and on. It has been temporarily disrupted by an abrupt wave of pressure given off by the flare. Such waves are known as shock waves.

Butterflies

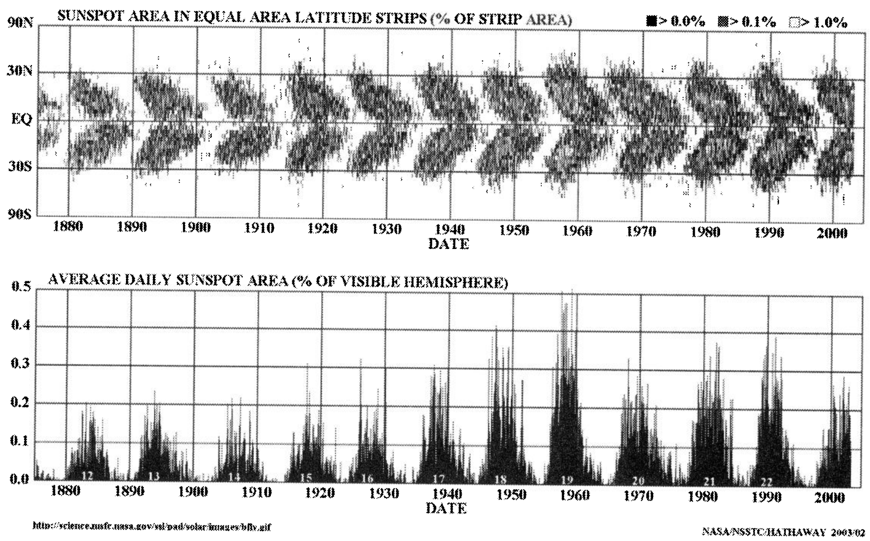
As we discussed, the sunspot cycle is caused by kinks in magnetic lines of force. As time goes on, the kinks go closer to the Sun's equator. Over the 11-year cycle, we can see the sunspots start at latitudes of about 50° north and south, and wind up at latitudes close to 10° north and south. (They seldom reach exactly the equator.)

About a hundred years ago, the British astronomer E. Walter Maunder plotted not only the sunspot number but also the latitude of the spots. For each vertical line on his graph, the latitudes where there are sunspots on a given day or in a given week or month are graphed. The horizontal axis shows the date.

Sun Words

The **butterfly diagram** is the graph that shows butterfly shapes when the latitude of sunspots is graphed over time.

Looking at Maunder's graph, or updated versions of it, shows how the sunspots start at high latitudes and wind up at low ones. As they reach low latitudes, the next sunspot cycle starts at high latitudes. For reasons that are obvious while looking at the graph, it is known as Maunder's *butterfly diagram.*



The butterfly diagram, showing the change over the sunspot cycle of the latitude at which sunspots appear.

(NASA's Marshall Space Flight Center)

The butterfly diagram is kept up to date in various places, notably on the web by David Hathaway of the Marshall Space Flight Center in Huntsville, Alabama. See science.msfc.nasa.gov/ssl/pad/solar/sunspots.htm for the latest graphs of the sunspot cycle and of the butterfly diagram. Hathaway also includes predictions for the rest of the sunspot cycle. His diagram shows that we should reach sunspot minimum in 2007. Sunspot maximum should then follow five or six years later.

Fun Sun Facts

Helios was the Sun god in Greek mythology. So, *heliosphere* merely means "the sphere of the Sun."

The Least You Need to Know

- Each sunspot has a dark umbra surrounded by a lighter penumbra.
- Sunspots are about 2,000 kelvins cooler than the surrounding photosphere.
- The sun rotates on its axis in about 25 days at the equator and slower toward the poles.
- The sun's differential rotation causes sunspots.
- The polarity of sunspot that leads in each hemisphere switches every 11 years.
- As the sunspot cycle wears on, sunspots appear closer to the equator.