Chapter 20

Ringing Like a Bell

In This Chapter

- Waves galore
- Sunquakes
- Seeing around the back
- The world is round

Advances in astronomy often follow technology. Things that were discovered in small quantities and with great difficulty using older techniques can now be studied in large quantities and, though still with difficulty, straightforwardly. The study of waves on the Sun follows this pattern. Discoveries made decades ago with film turn out to have widespread and major importance. They are now followed minute to minute with electronic detectors.

Images, Plus or Minus

Images have been made on film for over a century, but those images are relatively difficult to manipulate. Nowadays, more people are using scanners and Adobe Photoshop or similar programs to manipulate the images they take. But in the 1960s, it took some ingenious work at Caltech to make the significant manipulations that led to important discoveries around the Sun.

Robert Leighton, Robert Noyes, and George Simon realized that parts of the solar surface went up and down with a period of five minutes. They had discovered a "five-minute oscillation."

For years, the five-minute oscillation seemed like a curiosity. Theoreticians worked on understanding the sizes and motions on the Sun that could lead to such a period. But at first there was no inkling that the oscillating motions on the Sun were a widespread phenomenon.

For one thing, it is hard to study the Sun for extended periods of time. The seeing varies, for example, and images taken under poor conditions of seeing are hard to compare with images taken under good conditions. Furthermore, the Sun sets at night, so it is difficult at a given site to take images for more than 12 hours or so (somewhat longer in the summer). And telescopes differ enough from each other that it is usually difficult to compare in great detail images taken with different telescopes.

Solar Scribblings

An ingenious way of getting long periods of solar observations is to go near one of Earth's poles, where the Sun never sets for months on end. An early attempt was in Thule, Greenland, where a run of 60 consecutive hours of sunlight was obtained before clouds moved in. Later, long runs of solar observations were taken with a telescope at the South Pole.

Different techniques have been used to measure velocities on the Sun. The most accurate way is to use a spectrograph to measure a spectrum. The spectral lines are shifted to the blue when gas on the Sun is approaching, and shifted to the red when gas on the Sun is receding. But these shifts are relatively small for common motions on the Sun, so accurate techniques were needed to measure them. Use of an iodine cell, an iodine-filled container with transparent ends, enabled accurate measurements of motions.

Analysis of the long runs of data revealed that waves of many different periods were occurring on the Sun. Not only were there five-minute oscillations, but there also were oscillations many hours or days long. The longer the trains of uninterrupted data were, the more it was possible to detect the oscillations of longer periods. It became clear that major projects should be started to obtain solar velocity data all the time.

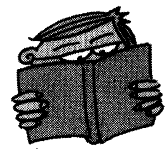
Fun Sun Facts

Although iodine is an excellent antiseptic, something to put on your finger when you cut it, it turns out to have been key in discovering more than 100 new worlds. The vapor of iodine, one of the chemical elements, has an absorption spectrum of very sharp spectral lines. When a tube containing iodine vapor is placed in the outgoing beam of starlight from a star under study, the vapor superimposes sharp absorptions at known wavelengths. These sharp iodine absorptions allow the wavelengths of absorption lines from the star itself to be measured to the fantastic accuracy of 3 m (10 feet) per second. Measurements to this accuracy have led to the discovery that the spectral lines from over 100 stars are moving in wavelength in a periodic fashion, revealing that the stars are being orbited by planets. A thorium comparison spectrum, as of 2003, is providing even better accuracy, to 1 m/s (3 feet/s).

Devastation on the Richter Scale

Waves that travel through Earth are known as *seismic waves*. Scientists measure the earthquake waves with devices called *seismometers*. Seismic waves spread through Earth and can be measured at various distances. Seismometers at different locations measure the waves they receive from an earthquake; by triangulating, scientists can figure out where the earthquake was and how strong it was.

Waves that spread through Earth can be useful, especially when they are not strong enough to cause damage. Changes in the speed at which the waves propagate reveal conditions under Earth's surface, where we can't see directly. So *seismology* on Earth, the study of seismic waves, is used to map out Earth's interior. By analogy to terrestrial seismology, the use of waves on the Sun to map out the Sun's interior is known as *helioseismology*. Waves on the Sun move at speeds of about half a kilometer per second. A full wave may let part of the Sun rise and fall over a distance of about 40 km (25 miles).



Sun Words

Seismic waves are vibrations that travel through Earth.

Seismometers are devices used to measure seismic waves on Earth.

The study of seismic waves is known as **seismology.**

The study of waves on the Sun and their use in mapping the solar interior is known as **helioseismology.**

Solar Scribblings

Chinese scientists thousands of years ago invented a simple seismometer in which balls rested insecurely on surfaces. When the ground shook, the balls fell off. Today's seismometers still use objects that are free to shake when the ground shakes.

In and Out

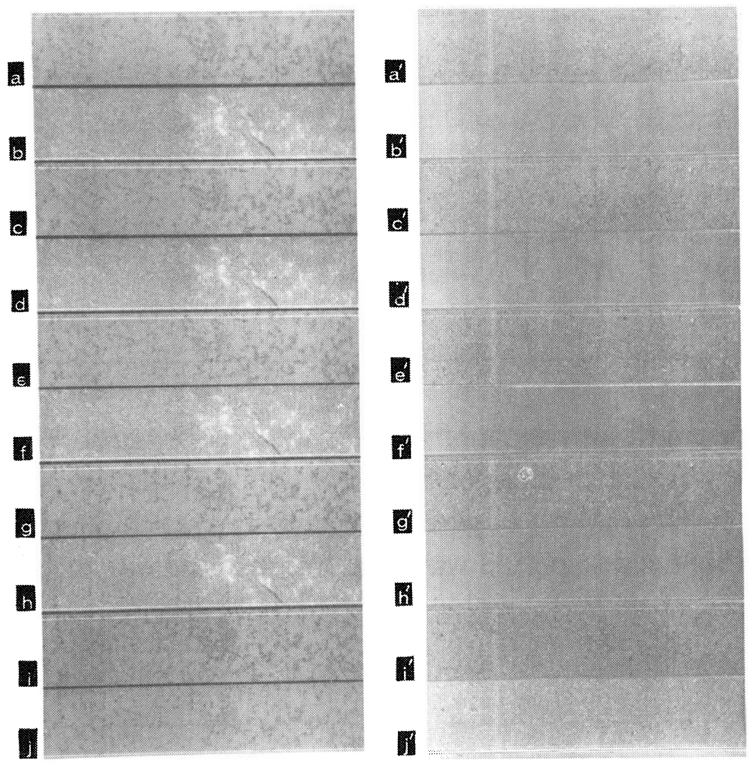
When I was growing up in New York, kids traditionally played with pink rubber balls called Spaldeens. (Their actual name was Spalding, but don't try to tell that to New York kids who grew up in a certain era.) When you were waiting to bat or throw, you could squeeze the ball in your hand. The difference between squeezing balls side to side and both side to side and top to bottom simultaneously illustrates differences between the ways that the Sun oscillates. Helioseismology studies the types of ups and downs of the solar surface and the large-scale patterns they have.

Solar Scribblings

Planets and their moons are squeezed in different directions. The most prominent example is Jupiter's moon Io, which is squeezed this way and that by gravity from Jupiter and the other major moons. The squeezing has heated up Io's interior, leading to extensive volcanism. But the Sun is heated so much by nuclear fusion that any effect of squeezing is negligible for heating, and the solar oscillations are generated by waves inside the Sun rather than by outside sources.

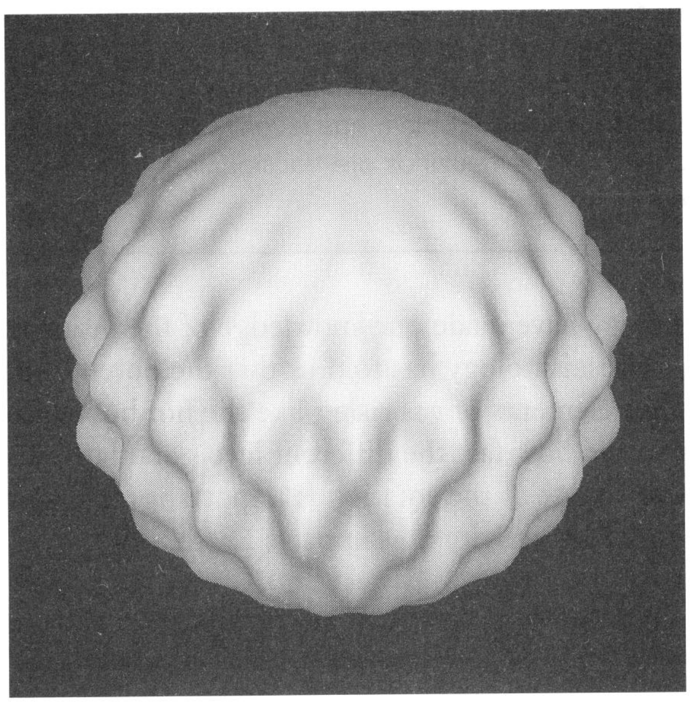
Solar seismologists categorize the waves by how many wavelengths it takes to fit once around the Sun. Since the Sun rotates, the direction around the equator is spinning and things relative to the equator can be different from measurements perpendicular to the equator. So you can speak of a type of wave that has a wavelength of, say, 50 times around the Sun's equator but only 10 times from pole to pole. Each type of wave can be assigned numbers for these two types of wavelengths. Note that we are talking about the Sun's whole surface moving in and out, with areas moving inward adjacent to areas that are simultaneously moving outward. A whole lot of different types of waves are all going on at the same time.

The surface oscillations are caused by sound waves generated by the convection that we see on the surface as photospheric granules. These waves are trapped inside the Sun, setting the solar surface vibrating. Since sound waves are variations in pressure, these waves are known as p-modes. As the waves in the solar interior move inward, they are bent by the changing speed of sound, which results from the rising temperature. As a result of the bending, the waves wind up hitting the surface. The rapidly decreasing temperature and density there cause the wave to be reflected back downward.



A set of images of part of the Sun made at Caltech in the 1960s as part of the work that led to the discovery of the five-minute oscillations. The images at the right show the velocities that result from subtractions of pairs of images on the left. Parts a, c, e, g, and i show redshifted gas and b, d, f, and h show non-moving gas. Subtracting pairs of these gives the images on the right, which show velocity. Parts a' and g', taken five minutes apart, look more alike than other parts, revealing a five-minute oscillation.

(A. Title, Lockheed Martin Advanced Technology Center)



One of the many modes of oscillation, with the extent of the excursion of the solar surface magnified over 1,000 times.

(NASA's Marshall Space Flight Center)

Solar Scribblings

When you tune your radio, you are picking just one set of wavelengths from the air. All the different wavelengths are around us all the time, with the radio spectrum invisible to us. But with the right electronics, we can pick up any given station. Similarly, the Sun has thousands upon thousands of different wavelengths going on all the time, and the task of helioseismologists is to pick out individual ones for study from the cacophony of what is always going on.

Depending on the wavelength, waves penetrate into the solar interior for different distances. Short-period waves, like those of the five-minute oscillation, are limited to regions near the Sun's surface. Waves of periods of hours go much deeper. Therefore, it is desirable to study the longest-period waves in order to find out about the Sun's deep interior.

The Solar Scoop

The longest-period waves have taken us to the deep interior, close to the region where nuclear fusion is fueling the Sun. They reveal the temperature in this region. Knowing the temperature is important for predicting the rate at which the nuclear reactions go on. In turn, that rate tells us the number of neutrinos that should be emitted from the Sun each second. Since we know our distance from the Sun, we can easily transform that rate into the number of neutrinos that should pass each square meter of Earth each second. As we have seen, this predicted number differs by a factor of about 3 from the number observed. This solar neutrino problem has recently been solved by the realization and proof that two thirds of the neutrinos are transforming themselves into other, previously undetected types.

Results from helioseismology have made our knowledge of the inside of the Sun more accurate. For example, helioseismology has told us that the outer 30 percent of the Sun is convective, with hot elements of gas rising like the hot bubbles of boiling water. Helioseismology has revealed how fast the different levels and latitudes of the Sun's interior are rotating. Knowledge of the rotation is important for understanding the formation of sunspots and solar activity that impacts Earth.

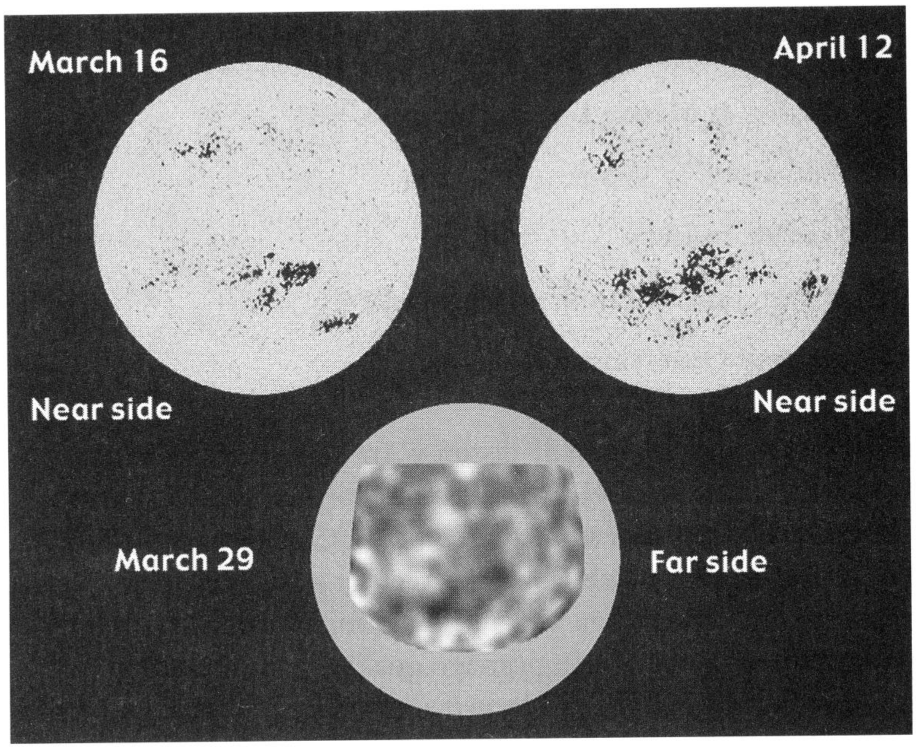
What's Behind?

When we look at the Sun, we see only half of it at a time. The other half is around the back. Since the Sun rotates about once a month, a bit of the surface on one side has just disappeared, but the part of the surface that is about to rotate into view hasn't been seen for about two weeks. It could have changed drastically during that time. Maybe an active region is about to appear and shoot off lethal particles at us on Earth.

Sometimes loops of gas stick up off the solar surface far enough that we can see them a day or so in advance, even though their base is on the far side. But we cannot directly see active regions farther around on the back, even though particles that they eject into space can curve around to hit us.

Helioseismology provides a way to get at least a rough view of what might be on the Sun's far side. Waves from far-side active regions travel through the Sun and affect oscillations that we see on the side of the Sun facing us. In essence, these waves make the Sun transparent.

To make the necessary calculations to trace back oscillations of our side of the Sun, we need very detailed observations. These have been provided by the MDI instrument aboard NASA and the European Space Agency's SOHO spacecraft, which we discuss in more detail in the next chapter. MDI routinely measures a million points on the side of the Sun facing us. After the waves are released by a sunspot region on the far side, the strong magnetic field in that region speeds up the waves passing through it. These waves pass through the Sun, as a result, about 12 seconds faster than other waves, compared with the overall travel time of about 6 hours.



The blurry image at lower center is an active region on the Sun's far side and is otherwise invisible except for this helioseismology method. This region is at the center of the Sun's disk two weeks before (upper left) and two weeks after (upper right) its far-side imaging, and the images show how rapidly it changes.

(Charles Lindsey, Solar Physics Research Corp., and Douglas Braun, NorthWest Research Associates)

'Round the World in Six Stops

As you learned in Chapter 3, the U.S. National Solar Observatory has set up a Global Oscillation Network Group, GONG. It got its name because it is studying how the Sun is ringing like a bell or a gong. (Rather than ringing from a single note and from a single strike, though, the Sun's ringing is more like linked bells hit by a sandstorm.) A bell or gong gives off sound waves, and the Sun's surface vibrations show the presence of similar waves there. From helioseismology, some of the waves are more significant than others. Studying all the waves together tells us about the solar interior, but it is important to get the longest possible complete runs.

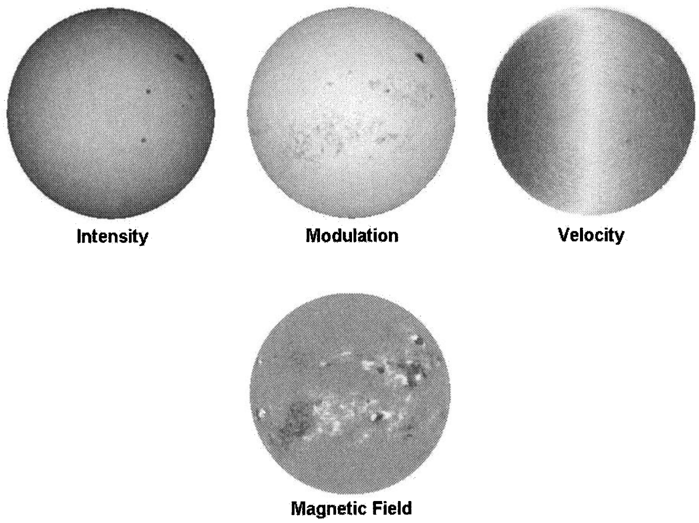
The U.S. National Solar Observatory heads the GONG project. Six telescopes spread around the world give coverage over 90 percent of the time. Each has an identical set of instruments and is fed by identical telescopes. For some of the wave studies, all the light from the Sun is considered together, without resolving individual surface features. The GONG telescope is only 8 cm (3 inches) across. The instruments record solar data every minute.

At each site, a pair of mirrors reflects the sunlight into a trailer, which houses all the instruments. Construction of identical trailers took place in the United States, after which the complete instrumental setups were shipped to the sites all over the world.

The six sites, all in operation for over half a dozen years, are listed here:

- Big Bear Solar Observatory, in California, USA
- High Altitude Observatory, at Mauna Loa in Hawaii, USA
- Learmonth Solar Observatory, in Western Australia
- Udaipur Solar Observatory, in India
- Observatorio del Teide on Tenerife, in the Canary Islands
- Cerro Tololo Interamerican Observatory, in Chile

Electronic capabilities have advanced in the half-dozen years since deployment of instruments at the GONG sites, and in 2001 upgrades transformed the setups into what is called GONG+. GONG+ uses electronic detectors (CCDs) that are 1,024 pixels square—a total of over a million pixels. These detectors give pixels that each correspond to 2.5 arc seconds on a side when viewing the Sun, allowing features about 5 arc seconds across to be imaged. Seeing (image quality) is not much better than that, typically, so it was not thought useful to provide a larger telescope or make other modifications.



The different kinds of solar data available from GONG++. We see the overall intensity that is observed; the variations of brightness from point to point (modulation) after various slowly varying backgrounds are removed; the overall velocity field, reflecting the sun's rotation; and the magnetic field.

(David Hathaway, NASA's Marshall Space Flight Center)

Helioseismology has provided us with an astonishing number of parameters about the solar interior. They include the ranges and position maps of temperature, density, the speed of sound, and the velocity of rotation. With GONG++, we will now have continuous measurements of the changing flows beneath the surface, that we call "solar subsurface weather." We have also learned the depth of the boundary of the convection zone, the total abundance of the elements heavier than hydrogen compared with that of hydrogen, and the abundance of helium, the second-heaviest element and a key to cosmology. Though it wasn't obvious until it was discovered, helioseismology is an extremely fruitful method of studying the Sun. It is now being applied as well to more distant stars, though to a lower level of accuracy because the stars are so much fainter.

The Least You Need to Know

- The Sun's surface is bouncing up and down, ringing like a bell.
- Analyzing the surface motions reveals the conditions of the Sun's interior.
- Waves on the near side reveal even sunspots on the Sun's far side.
- A network of solar telescopes spread around the world gives nearly continuous coverage.