Chapter 3

Seeing the Invisible

In This Chapter

- Why we don't see right through the Sun
- How parts of the spectrum other than visible light help us learn about the Sun
- How solar seismology tells us about the Sun's inside
- Why the Sun shines
- How neutrinos escape from the Sun's center and tell us about it and about themselves

When we look up at the Sun, we see right through the chromosphere and corona. That's why we see the photosphere, even though those layers are between it and us. They are just invisible to us because they are too thin and insubstantial.

Invisibly Transparent

Imagine that you are in a smoky room (thankfully, something that is becoming rarer). The smoke may be so dense that you can't even see people on the far side of the room. But what if someone walks over to you from there? Halfway over, he or she may become visible. So the smoke has optical thickness but isn't entirely opaque.

Astronomers use the idea of optical thickness to explain how much they see through a gas. When a gas has optical thickness of zero, then it has no optical thickness and is completely transparent. Read on to see what it means for optical thickness to be greater than zero.

A couple important and interesting numbers come up all the time in mathematics. One is π (pi), which stands for the ratio of the circumference of a circle to its diameter. It is approximately equal to 3.14159265358979323 ... and cannot ever be expressed exactly as a decimal. In mathematicians' terms, that makes it an irrational number. The other important irrational number is *e*, which is approximately equal to 2.71828459045 ..., and which for our purposes, we can think of as "about 3."

Fun Sun Facts

As of 2003, more than a trillion places of pi have been calculated, confirming that no pattern in the digits exists, at least up to that point. The calculations are carried out in large part to test computer methods.

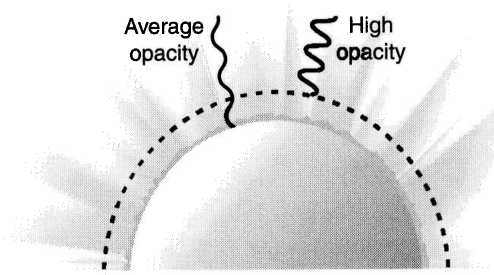
Sun Words

A gas's **opacity** is a measure of how opaque—not transparent—it is.

For an astronomer, a gas has an optical thickness of 1 when the intensity of the light that gets through is reduced by a factor of the special number *e*, which is about 2.7. A gas has an optical thickness of 2 when the intensity of the light that gets through is reduced by a factor of $e \times e$, which is about 8. So if gas between you and something has optical thickness of 2, only about $^1/_8$, or about 10 percent, of the light gets through. Even less gets through optical thickness of 3, and for higher optical thicknesses, it is hardly worth considering the tiny amount of light that gets through. The total *opacity* of the gas is increasing as we look through more of it.

This calculation of optical thickness means that we see into the Sun until the gas between it and us gets to about optical thickness of 2 or so, and we don't see anything of optical thickness less than about $^1/_2$. In fact, for many purposes, we can consider the photosphere as occurring at optical thickness of $^2/_3$.

But optical thickness of $^1/_2$ up to 2 occurs in the photosphere only when we are considering all the light from the Sun together, which we call *white light.* If we look through a special filter that shows only certain colors that have higher optical thickness, then the optical thickness piles up to be noticeable before we reach the photosphere, looking down. In particular, if we use a red filter that passes only the red light from hydrogen, there is so much hydrogen on the Sun that we reach optical thickness 2 while we are still in the chromosphere. So the chromosphere becomes visible to us, even with a telescope on Earth, and we have found a way of overcoming its general transparency.



The depth at which we stop seeing into the Sun depends on the color of the light.

Once we have used this filter, we can use ordinary cameras—film or electronic—to take images. The light that comes through is in the visible, and film and electronics are sensitive to it. We merely leave out all the other colors of light that hide this color.

Fun Sun Facts

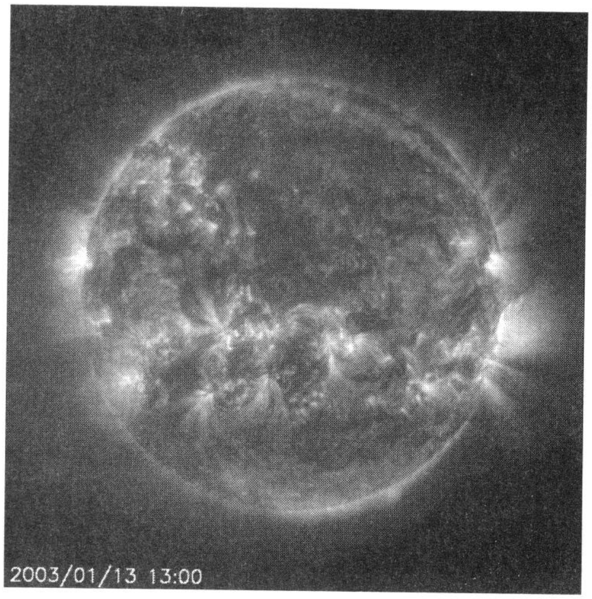
If we look through some gas and its optical thickness is less than about a half, the gas looks transparent to us. But if we look through some gas whose optical thickness is greater than about 2, it looks opaque. So the question why the Sun has a sharp edge is related to the following: What is the angle near the edge of the Sun, when looking from Earth, between a line of sight that has an optical thickness of $^1/_2$ and a line of sight that has an optical thickness of 2?

The answer to that question is that the angle is very small—smaller than we can see with our unaided eye. So the Sun goes from transparent to opaque over an imperceptibly small angle for us, and the edge of the Sun looks sharp.

Invisibly Radiating

Light, the term we use for optical radiation, has a few special colors that allow us to see the chromosphere. These colors correspond to hydrogen gas in the red or blue and to calcium gas in the violet, just on the edge of ultraviolet. If we look through filters that pass only these specific colors, the Sun's gas can be more opaque. With this higher opacity, we stop seeing at higher heights.

If we look at certain wavelengths that the SOHO or TRACE spacecraft use, the photosphere does not emit strongly and we see coronal gas silhouetted against a dark background, even though its total opacity is not high. Again, we have used special techniques to reveal what was otherwise invisible.



An image taken by the SOHO spacecraft's Extreme-ultraviolet Imaging Telescope through a filter that passes only a narrow set of wavelengths in the ultraviolet. The image shows the solar corona; the background photosphere doesn't radiate much at this wavelength.

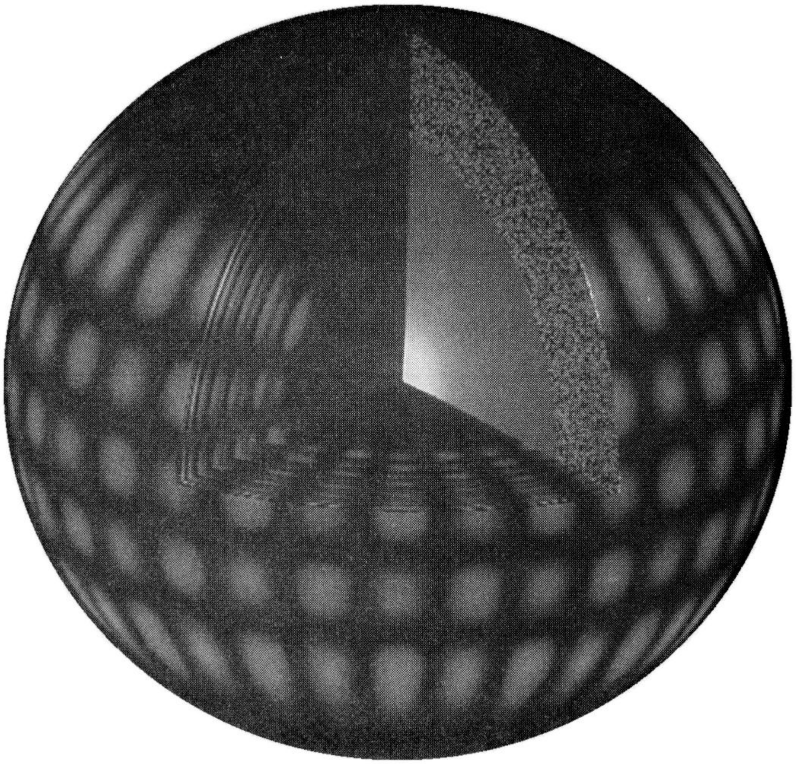
(EIT Team, NASA's Goddard Space Flight Center)

Invisibly Central

Below the photosphere, things are invisible for a more fundamental reason: Our view of them is blocked by the photosphere itself. We can't see down to the center of the Sun, and certainly not down to its core, in ordinary light. Even x-rays or radio waves don't go through the photosphere, so they aren't of any help in studying the core.

Solar astronomers now study the center of the Sun by using a technique used by geologists and other geoscientists on Earth. They use a type of earthquake wave. On Earth, geologists can't peer through the Earth's crust, but they use devices called seismometers to measure waves that are caused by earthquakes and other disturbances. As those waves pass through parts of the Earth, they are changed and distorted. By measuring the earthquake waves that reach a seismometer—or, better, a network of seismometers spaced around the Earth—geoscientists can tell what structures the Earth had between the earthquake and their measuring instruments.

Similarly, solar astronomers can measure waves on the surface of the Sun. They do this by taking pictures of the Sun every few seconds. By comparing the brightness and velocity of individual bits of sunlight—individual pixels—they can tell how each bit of the Sun changes over time. They then use some standard mathematical methods to discover what periods of waves are involved.



Calculations show that large areas of the Sun are moving up and down, and that the period of the oscillation depends on the size of the regions.

(National Solar Observatory, NOAO/AURA/NSF)

Since similar methods on Earth are called seismology, the work on the Sun is called "solar seismology," or *helioseismology*. Over the last two decades, helioseismology has grown to be a major part of solar astronomy. It has found that the Sun vibrates with various periods—that is, it rings like a bell.

One problem with helioseismology is that the Sun sets at night. To find out what waves of long periods—hours or days—exist on the Sun, you have to observe for long periods consecutively. Having the Sun set in the middle ruins your stream of data. The problem has been solved in two ways.

> **Sun Words**
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> **Helioseismology** is the science of finding out about the inside of the Sun by studying oscillations of the Sun's surface.

The first way is just to find a way to keep the Sun from setting—figuratively, at least. The solution started decades ago with observations made from the U.S. base at Thule, Greenland, where at certain times of year, the Sun doesn't set. Fighting clouds and weather, consecutive runs of 80 hours and later longer were achieved.

A second way to keep the Sun from setting is to distribute telescopes around the Earth. After all, it used to be said that the Sun never set on the British empire. Now the Sun never sets on the identical telescopes of the Global Oscillation Network Group. The group's initials spell GONG, which is suitable for something that is finding vibrations with a variety of periods. (We will say more about it in Chapter 20.)

Fun Sun Facts

Sometimes professionals who study the Sun are called solar astronomers, but even more often they are called solar physicists. The two terms come from the origin of the study at the turn of the twentieth century. People who studied the Sun tended to come from the physics population, perhaps because they were studying the Sun's spectrum or using techniques like infrared. Astronomers of the time tended to study where the stars were, and they worked at night instead of in the daytime. The term "solar physicist" stuck. To this day, the main professional journal in the field is called *Solar Physics*.

The GONG group is an international consortium based at the National Solar Observatory in Tucson, Arizona. It has identical telescopes spaced around the world, in places such as Udaipur, India and Learmouth, Australia. It has now operated for several years and has continuous chains of observations that are months long. Version GONG++ upgraded the original telescopes to take data more often and on a finer scale of spatial resolution—that is, able to see finer details.

A third way of keeping the Sun from setting is to go out into space. The SOHO spacecraft sits a million miles above Earth in the general direction of the Sun. We say that it is in a "halo orbit," in that it moves in a small halo-like circle around a point between the Earth and Sun where the gravity balances. If it were directly between the Sun and us, we couldn't get data back from it because the background static from the Sun would overwhelm the spacecraft's radio.

SOHO carries three instruments that do helioseismology. From its position in space, the Sun is always visible, so the instruments make continuous sets of observations. Except for brief intervals when they malfunction, they work consecutively for months or years.

One of the results of all this helioseismology is that we understand the center of the Sun very well. We have learned how fast the Sun rotates at different distances from its center. These data have shown us how the Sun's differential rotation extends way down from the surface. We have also learned that the Sun has an outer zone and an inner zone. In the outer zone, convection carries energy upward. It does so in 1,000-km–size bits of gas in a manner similar to water boiling on a stove. Below the boundary, in the inner zone, radiation carries energy upward. Radiation is the process by which energy is carried by gamma rays, x-rays, ultraviolet, light (that is, visible light), infrared, or radio waves. (We usually say simply "ultraviolet" instead of "ultraviolet light" or "ultraviolet radiation" and, similarly, simply "infrared.") Gamma rays actually carry the energy in the Sun's central region. Helioseismology has told us accurately where that boundary is: about 72 percent of the way outward from the center to the surface.

Invisibly Blocked

Until recently, we could see what happened on only half the Sun at a time. That is, we could see the side that faced us, but not the other side. Of course, since the Sun rotates, some parts just rotated around the edge yesterday. But the part that will rotate around to the front side tomorrow hasn't been seen for about two weeks.

We still can't get good images of the far side, and we haven't (yet) sent a camera on a spacecraft to get such a view. But the techniques of helioseismology can be used to get fuzzy images of what active regions exist on the Sun's far side. So even a million miles of solar gas no longer stand in our way.

How and Why the Sun Shines

A hundred years ago, scientists knew that the Sun was hot, but they didn't know why. They had ideas of why, of course. They knew that when a big ball of gas contracted, it gained energy in the contraction from gravity. Perhaps this type of energy heated the Sun. They could calculate how long the Sun could live if it got its energy in this way. Its age couldn't be greater than a few million years.

But then scientists discovered by studying the Earth that rocks and fossils were billions of years old. It didn't make sense for the Earth to be older than the star around which it travels.

In the 1920s, the British scientist Arthur Eddington realized that energy could be released when atoms fused to make heavier elements. At first, Eddington and other scientists didn't know exactly how the atoms fused or which atoms did so, but they knew that nuclear fusion could release a lot of energy. It gave hope that nuclear fusion could fuel the Sun for the billions of years necessary to make the Sun older than the oldest rocks on Earth.

Fusion is the opposite of fission, in which energy is released as atoms split apart. Fission of uranium into lighter elements was identified in 1939. Fission is the process used in today's nuclear power plants.

In 1938, the physicist Hans Bethe was at Cornell University. (He was one of many scientists expelled from Germany, but he made his home at Cornell, where he was still writing scientific papers into the twenty-first

Fun Sun Facts

When the idea of nuclear fusion came up, some scientists doubted Sir Arthur Eddington's statements that it fueled the Sun. Eddington's reply? "We tell them to go and find a hotter place." Did he mean a star or Hades for the questioner?

century.) Bethe figured out certain ways in which atoms could fuse in the Sun and the other stars. Incidentally, it is so hot in the Sun that the atoms are torn apart, and it is really their central parts, their nuclei, that are fusing. So we could use the word *atom* or the word *nucleus* as we please.

One of Bethe's ideas was the *carbon cycle.* In it, an atom of carbon fuses with an atom of hydrogen. That transforms the carbon. One at a time, more atoms of hydrogen are added. Eventually, after four hydrogens have been added, we wind up with our carbon back again, but with a helium atom, too. If you compare the mass of everything that went in—four hydrogens and a carbon—with the mass of what you are left with—a helium and a carbon—you find that some mass has disappeared. It left the atoms in the form of energy.

Sun Words

An **atom** is the smallest building block of the chemical elements; a chemical element is one type of atom. Each atom contains a tiny **nucleus** in its center. The nucleus contains most of the atom's mass.

Sun Words

The **carbon cycle** is a way to fuel stars by adding hydrogens to a carbon atom and its intermediate transformations. It operates in stars hotter than the Sun. The **proton-proton chain** is the series of reactions that fuel the Sun.

In 1905, Albert Einstein showed that mass and energy are equivalent. He gave the formula for the conversion: $E = mc^2$, where E is energy, m is mass, and c is the speed of light, a large number. Einstein's formula shows us that even if only a little mass disappears, a lot of energy results. Bethe could show that the amount of energy that disappeared in the stars was enough to keep them shining for billions of years.

Though it wasn't clear at first, Bethe's carbon cycle doesn't operate in the Sun. It isn't hot enough. Instead, the *proton-proton chain* fuels the Sun. In it, protons come together, first a pair and then others adding to the result. At the end, again we have one helium atom instead of four hydrogens. And again, $E = mc^2$ shows us that we have gotten relatively a lot of energy from the disappearance or transformation of a little mass.

The Sun is so massive that it has a lot of hydrogen in it. The Sun contains 2 with 33 zeroes after it of mass as measured in grams. Since we multiply by 1,000 each time to go from one to a thousand to a million to a billion to a trillion, the Sun contains twice a billion trillion trillion grams of matter. And 90 percent of it is hydrogen. So even if only a bit of energy comes from each fusion of four hydrogens into a helium, there is still enough to fuel the Sun for 10 billion years. We are now halfway through that lifetime.

There was one legitimate objection to the idea that nuclear fusion could make the Sun shine. That is that all nuclei have positive charges. And pairs of positive charges repel each other. So how could you get two hydrogen nuclei together in order to allow them to fuse? The answer is in the incredibly high pressure at the center of the Sun, a result of all the mass above it being pulled together by gravity. And part of the answer is in the high temperature—about 15 million kelvins—at the center of the Sun. Helioseismology has verified our ideas about the high temperature and pressure deep inside the Sun.

Fun Sun Facts

Fusion, which takes place inside the Sun, is the opposite of fission. In fission, heavy elements such as uranium and plutonium divide into less massive elements. In fusion, light elements such as hydrogen combine to make heavier elements such as helium and carbon.

If you put too much of certain kinds of uranium or plutonium together, it makes an A-bomb (atomic bomb). But if you put a lot of hydrogen together, nothing happens unless you compress it and heat it up, perhaps with an A-bomb. Only if you do so will you get an H-bomb (hydrogen bomb).

There is another big difference: Uranium and plutonium are hard to get or make. Hydrogen is very plentiful—the oceans are full of it, since water is H_2O.

Invisible Neutrinos

Though electromagnetic radiation like gamma rays or light doesn't get directly to us from the center of the Sun, one kind of particle does. This subatomic particle is the *neutrino*, a term that means "little neutral one." The neutral part means that it doesn't interact with the Sun's magnetic field. More than that, neutrinos hardly interact with matter at all.

But neutrinos are formed deep inside the Sun, where the Sun makes its energy. The temperature and pressure are so high there that nuclear fusion takes place. And in some of the intermediate reactions, as hydrogens are fused into helium, neutrinos are given off.

Sun Words

A **neutrino** is a subatomic particle with very tiny mass and no electric charge that travels at almost the speed of light and interacts very poorly with other matter.

Neutrinos interact so seldom with matter, even with a Sun's mass of matter, that they almost all escape. Traveling at the speed of light, or almost so, they reach Earth in about 8 minutes.

Fun Sun Facts

John Updike wrote a poem about neutrinos called "Cosmic Gall." He began:

Neutrinos, they are very small.
They have no charge and have no mass.

The latest results, though, show that the last of his points is wrong.

But if neutrinos escape from the mass of the Sun so easily, how do we detect them on Earth? The answer is: with difficulty. The basic theory was figured out by the astrophysicist John Bahcall in the 1960s. He recruited the chemist Ray Davis to work out the way to detect neutrinos. Davis thought of and perfected a scheme using chlorine. When a neutrino hits a chlorine atom, it converts to a radioactive form of argon. Davis figured out how to collect small quantities of argon and to count the number of atoms.

Davis filled a huge tank with chlorine atoms. He let it sit out for weeks or months and then counted how many argon atoms had formed. Only one argon atom had formed every other day or so! He had incredibly sensitive techniques.

Fun Sun Facts

Davis needed 100,000 gallons (400,000 liters) of chlorine in liquid form, which he got most cheaply as ordinary cleaning fluid. Dry cleaners use so much of it that it is widely available and very cheap—cheaper than milk or the bottled water so many people drink. If you worked for a company that received such an order for cleaning fluid, would you send along thousands of wire hangers?

Davis's tank is a mile underground in the Homestake Gold Mine in Lead, South Dakota. Many scientists want to have the government take over the scientific facilities, making them into a major underground national observatory. Otherwise, the owners may well close the mine and therefore prevent access to the scientific area. It is important to have some experiments, like this one, underground to keep out random nuclei coming from outer space—the so-called "cosmic rays." Cosmic rays don't pass through a mile of rock.

Davis succeeded in detecting occasional neutrino collisions through finding his argon atoms. But he detected only about a third as many as Bahcall had calculated he should. Physicists attacked, saying that Bahcall's calculations were wrong. They said that he didn't know how hot the Sun's center was. Even a small error in the temperature would have a big effect on the calculation of how many neutrinos to expect.

But Bahcall kept refining his calculation. After an original substantial correction, his predicted value has remained fairly constant for decades. And Davis's tank keeps chugging on, collecting neutrinos from the Sun. The difference between the prediction and the observations was known as the solar neutrino problem. Davis shared in the 2002 Nobel Prize in physics.

Eventually, in the 1990s, some other methods of detecting neutrinos were worked out. One sensitive method used the element gallium instead of chlorine. It was sensitive to a wider range of neutrinos, since the chlorine atoms were sensitive only to neutrinos with very high energies. Large amounts of gallium were collected in the Soviet-American Neutrino Experiment (SAGE) in what is now the Russian Federation, and in GALLEX, the gallium experiment, in Italy. The Italian gallium is held in a side-cavern in a highway tunnel deep under a mountain. The gallium experiments also show too few neutrinos to match the predictions.

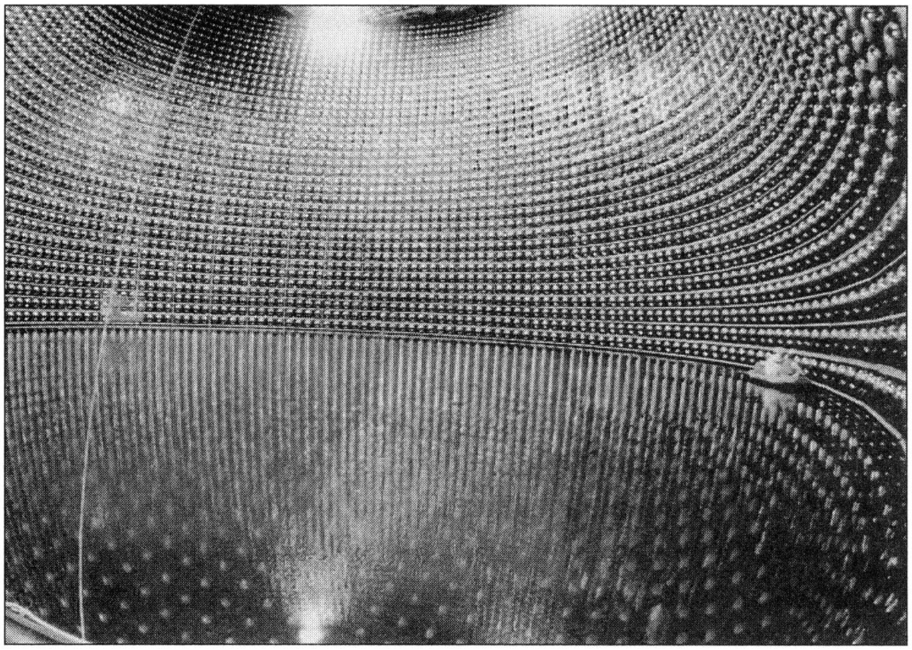
Fun Sun Facts

The rate of one detectable interaction of a neutrino in about a day and a half is known as 1 solar neutrino unit, or 1 SNU. In a paper that brought the solar neutrino problem up to date, the great physicist Willy Fowler titled it "What SNU?"

Another type of neutrino experiment was set up in the Kamioka mine underground in Japan. It is known as Kamiokande, for Kamioka Neutrino Detection Experiment. It used a huge tank of very pure water and looked for flashes of light as neutrinos interacted with protons in the water. It not only showed the deficiency in the number of neutrinos, but it also found evidence that neutrinos could change from one type to another. The head of the project, the Japanese scientist Mashatoshi Koshiba, shared half the 2002 Nobel Prize in physics with Davis.

This evidence that neutrinos can change types, known as "flavors," is proving to be the key to the solar neutrino problem. There are three types of neutrinos. The Sun gives off only one of those types, and that is the type that the neutrino experiments have been detecting. Now it seems that en route between the Sun and Earth, the neutrinos have been changing so that they are distributed among the three types when they arrive at Earth. Since the chlorine experiment detects only one of the types, it is no wonder that it detects only one third of the prediction.

To change types, physicists tell us, neutrinos must have some mass. Massless neutrinos couldn't change. So the evidence in the successor Super-Kamiokande experiment that neutrinos change types shows that they have mass, though it doesn't tell us how much. The discovery has the potential to change important things in nuclear physics. The physicists were premature in telling the astronomers that we had our Sun temperature wrong. They were the ones who were wrong, with their conviction that neutrinos were massless. The discovery that neutrinos have mass after all could lead to major revisions of nuclear theory.



The large tubes in the Super-Kamiokande experiment sense flashes of light given off when neutrinos interact in the tank of water. Since the photo was taken, the tank had been filled, but when it was emptied and refilled in 2002, many of the photomultipliers broke and had to be replaced.

(Kamioka Observatory, ICRR [Institute for Cosmic Ray Research], The University of Tokyo)

The best neutrino observatory was opened in 2001 in the Sudbury mine in Ontario, Canada. This Sudbury Neutrino Observatory uses "heavy water," water in which the ordinary hydrogens are changed to deuterium. Deuterium, known as "heavy hydrogen," has an extra, neutral particle in its nucleus in addition to the lone proton that ordinary hydrogen has. The deuterium is especially sensitive to neutrinos, and the scientists have been running various experiments to detect neutrinos as they undergo different types of reactions. They are pinning down the details of solar neutrinos.

The Least You Need to Know

- Gas has an amount of opaqueness, which we measure by optical thickness.
- Looking at the Sun through special filters or in nonvisible light can show us levels higher than the photosphere.
- Helioseismology, the study of surface waves on the Sun, tells us what the Sun is like inside.
- The Sun shines because hydrogen is fusing into helium at its core.
- The detection of solar neutrinos by several experiments has told us both about the Sun and about neutrinos themselves.