

# Yo Ho, SOHO

## In This Chapter

- ◆ SOHO carries a dozen instruments in orbit
- ◆ Several SOHO instruments study the corona
- ◆ SOHO provided a breakthrough in studying the Sun's insides
- ◆ Several SOHO instruments study the solar wind

Since Sputnik, many scientific instruments have been on satellites that orbit the Earth every 90 minutes or so. Furthermore, many weather satellites and other spacecraft are tens of thousands of miles high, appearing to hover over a given place on Earth. But a major spacecraft to study the Sun is in yet a different location: 1.5 million km (a million miles) away in the direction of the Sun. At that location, it remains fixed between the Earth and the Sun, retaining its excellent position for viewing. It also measures the influence of the Sun as it extends toward the Earth. For a decade, this spacecraft has been the best general observatory studying our nearest star.

## Europe and America Conjoined

NASA and the European Space Agency don't always see eye to eye. They had a joint plan to launch a pair of spacecraft called Solar Polar Mission to fly over the Sun's poles, but the United States dropped out. Only the

mission called Ulysses survived. On the Hubble Space Telescope, Europe is a junior partner, with 15 percent participation. But in the mission called the Solar and Heliospheric Observatory, the United States and Europe are really partners. If anything, as with Yohkoh, the United States is the junior partner.

### Fun Sun Facts

The mass of SOHO's instruments is about 600 kg (1,300 pounds), less than that of a small car. Altogether, SOHO weighs a couple tons—or, at least, it did while on Earth before it was blasted into the weightlessness of space.

The Solar and Heliospheric Observatory, known as SOHO, carries a dozen instruments aloft. Of the individuals who head the different instrument teams, known as principal investigators, nine are European and three are American. Hundreds of scientists collaborate. The spacecraft was built in Europe and launched by NASA. NASA now receives the spacecraft data through its Deep Space Network of radio telescopes.

Previous solar observatories were in low earth orbit, which meant that the Earth blocked their view of the Sun for part of every 90-or-so-minute orbit. But full-time viewing is an advantage for many reasons, including the ability to obtain the long, continuous series of data that is useful for helioseismology. So SOHO was sent 1.5 million miles upward to a place known as the L1 Lagrangian point. There the net of the Earth's gravity and the Sun's gravity balance the centripetal force related to the speed and size of the orbit. As a result, SOHO can remain in place, orbiting the Sun with the same period as the Earth, while expending relatively little fuel.

### Fun Sun Facts

SOHO isn't directly in line between the Earth and the Sun because, if it were, the Sun's radio emission would provide so much static that we couldn't get data from the spacecraft. Instead, it uses a bit of fuel to fly in a small circle around the point that is actually in line. The appearance of the small circle leads astronomers to say that SOHO is in a halo orbit.

SOHO was launched on December 2, 1995, from NASA's launch pad at Cape Canaveral, Florida. It was launched on an unmanned rocket. An attached Centaur rocket placed it into a circular orbit around the Earth. A second burn of the Centaur rocket then sent SOHO farther out into space, for the four-month trip toward its goal.

Dramatically, on June 25, 1998, a set of routine tests went wrong. Because of a human programming error, a computer program kicked in at the wrong time, and the spacecraft went spinning out of control. As SOHO lost power, the instruments and even

the fuel chilled and everything stopped working. It took months before engineers on the ground could regain control, as the spacecraft's orbit changed enough for the solar panels to generate more electricity. Finally, and almost miraculously, all the instruments but one started up again. SOHO resumed its scientific mission and has worked flawlessly since then.

## SOHO's Coronal Science

SOHO's instruments fall into separate categories. Some study the Sun's outer atmosphere. Some study the Sun's interior by observing the photosphere and using helioseismology. Others study the outflow of particles from the Sun known as the solar wind.

Since SOHO was launched at solar minimum and now has lasted through solar maximum, its instruments have given us a good view of how the Sun changes through the solar-activity cycle.

## LASCO Blocks the Center

One of the simplest experiments on SOHO to follow involves a set of three telescopes. Each is a coronagraph. The inner one, now defunct, was an all-mirror coronagraph. Like traditional coronagraphs, it blocked the solar photosphere inside the telescope. However, it differed from the traditional design by not using lenses. The outer two LASCO telescopes, still operating well, are externally occulting coronagraphs. That is, a disk suspended in front of each telescope blocks the incoming light from the photosphere.

Each type of coronagraph—internally occulting and externally occulting—has its own set of problems. The innermost coronagraph, known as C1, had mirrors that were polished so carefully and so smoothly that they were known as superpolished. Nonetheless, the amount of light scattered in the coronagraph was enough to be troublesome. In any case, this was the only instrument that did not start working again after SOHO was saved from its spin-down.



### Solar Scribblings

Astronomers have invented a robot to superpolish telescope mirrors. It monitors a mirror's surface to search for imperfections and programs the way in which the surface could be better smoothed. This technology may be applied to artificial knee joints: The lifetime of current artificial knees is limited by grinding in the joint, and superpolishing may help.

The other two coronagraphs show part of the corona very well, but they can't show the innermost part. The occulting disks in front of the telescopes are not in focus, since the telescopes must be focused at the Sun, which is millions of miles away. To properly hide the photosphere, the externally occulting coronagraphs must also hide the inner corona.

The C1 coronagraph showed the corona from 1.1 solar radii out to 1.5 solar radii. That is 1.5 times the radius of the Sun, which is almost 700,000 km (about half a million miles). The C2 coronagraph shows from about 1.5 solar radii out to 6.9 solar radii, while the C3 coronagraph shows from 3.5 solar radii out to 33 solar radii.

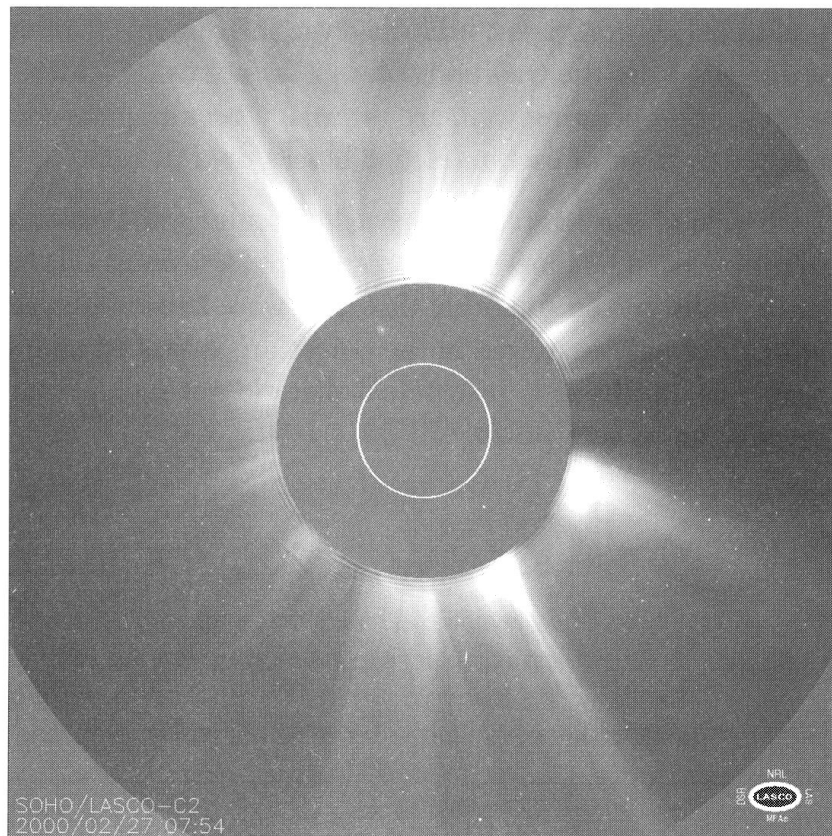


### The Solar Scoop

Solar astronomers often measure distance into the corona in terms of the Sun's radius. If something is at 1.5 solar radii, it is half again the distance from the center of the Sun to its edge. This distance, the solar radius, is 700,000 km (420,000 miles). When the C3 coronagraph observes to 33 solar radii, it is seeing out around 22 million km (14 million miles) into space. This distance is a fair fraction of the 150 million km (93 million miles) of separation of the Sun from Earth.

*The Sun seen with LASCO's second coronagraph, known as C2, which covers from about 1.5 to about 6.9 solar radii of corona.*

*(Naval Research Laboratory)*



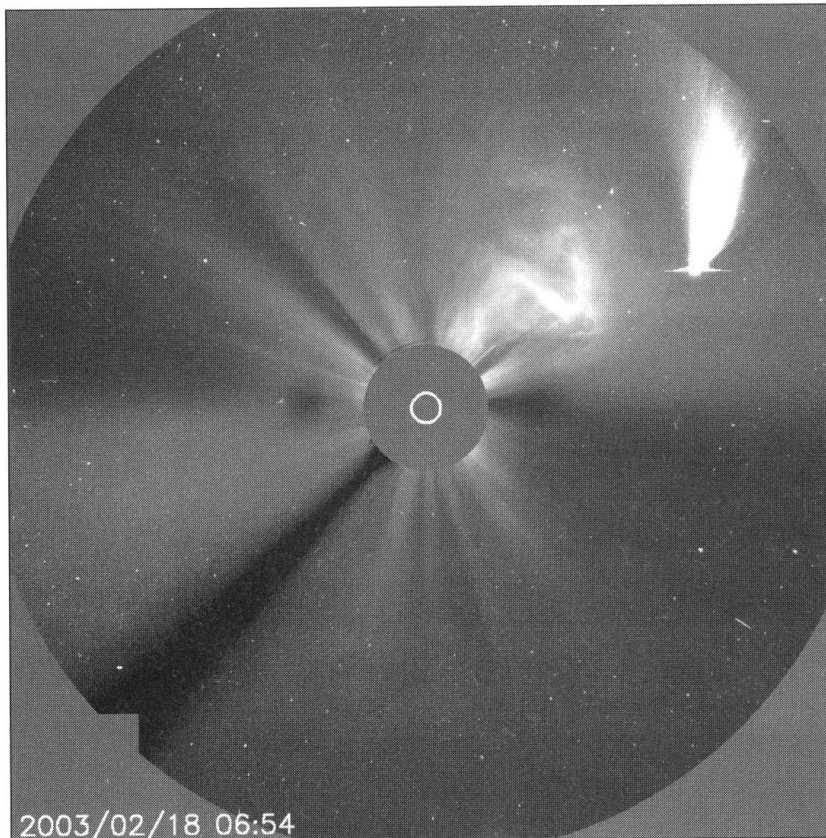
These coronagraphs have shown an astonishing phenomenon: Huge eruptions of mass occur about every day. As a result of this mission, these *coronal mass ejections* have been identified as a major source of the Sun's influence on the Earth. Watching the coronal mass ejections can even give warning hours or days before an eruption affects the Earth's magnetic field as well as satellites in orbit around the Earth.

Surprisingly, SOHO's coronagraphs have also led to the discovery of hundreds of comets. Many of these comets belong to a specific group of comets with very elongated orbits whose close point to the Sun is very close indeed. Sometimes these comets hit the Sun and disappear.



### Sun Words

A **coronal mass ejection** is the eruption and departure from the Sun of a piece of the corona. These ejections, often called CMEs by professionals, have been seen near solar maximum to occur daily. They are a major link between the Sun and the Earth.



*A comet passing near the Sun, seen in LASCO's C3 coronagraph. The comet is C/2002 V1 (NEAT), the brightest comet seen by SOHO. The sun coincidentally gave off a coronal mass ejection during this part of the comet's closest approach. The overexposed comet nucleus caused the horizontal line of pixels that extend from it to appear bright. The size of the Sun is drawn onto the dark occulting disk for scale.*

*(Naval Research Laboratory and NASA's Goddard Space Flight Center)*



### Solar Scriblings

One of the first comets seen in a space coronagraph to disappear behind the occulting disk apparently hit the Sun. Soon thereafter, an apparent spray of material appeared from the other side of the occulting disk. People assumed that it was spray from the comet material. But now that we realize how often coronal mass ejections occur, it was probably merely an unconnected and coincidental coronal mass ejection.

## Going to Extremes

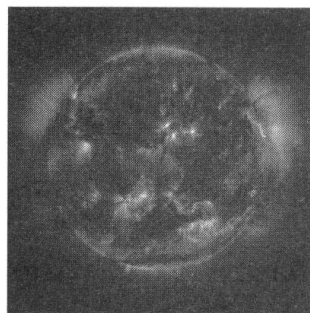
One of the instruments on SOHO looks at the Sun in the spectrum between x-rays and the visible. That region, in general, is known as the ultraviolet. However, this instrument looks at the end farthest from the visible and closest to the x-rays. That part of the spectrum is often known as the extreme ultraviolet, sometimes written as XUV or EUV. The instrument is the Extreme-ultraviolet Imaging Telescope (EIT).

EIT carries a set of four filters, each of which is optimized for viewing some particular temperature region on the Sun. By comparing the four images, we can see how the temperature of the solar corona increases with height above the photosphere. Each of these filters is in the extreme ultraviolet.

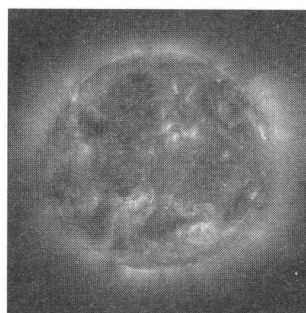
*A comparison of solar views through the four different filters aboard SOHO's Extreme-ultraviolet Imaging Telescope (EIT).*

*(NASA's Goddard Space Flight Center/EIT Science Team)*

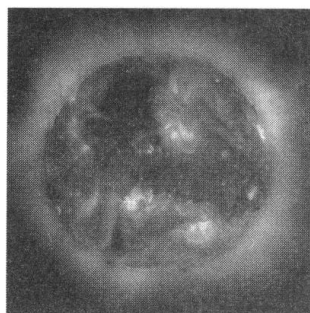
171Å  
1 million °C



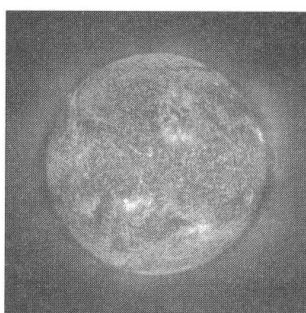
195Å  
1.5 million °C



284Å  
2-2.5 million °C



304Å  
60,000 °C



The lowest temperatures are shown in the filter at 304 Å. (Remember that the lower end of visible light is at about 4,000 Å.) This filter passes primarily radiation from helium that has lost one electron. (We say that the helium is ionized or, for clarity, once ionized.) For that to happen, the temperature must be about 100,000°F (60,000°C). This temperature is about 10 times hotter than the solar photosphere but is still much less hot than the corona. It is the hottest sort of chromospheric gas. (Note that at these high temperatures, °C and kelvins are indistinguishable.)

The next lowest temperatures are shown with the filter at 171 Å. This filter passes light from eight- and nine-times ionized iron. The gas that we see through this filter is about 1,800,000°F (1,000,000°C) and is from the corona. We see particular coronal hotspots, which are located over sunspots in particular and active regions in general. We also see a diffuse background, including the bases of some of the stronger streamers.

Somewhat higher temperatures appear in EIT's third filter, at 195 Å. The gas that we see is from Fe XII and is therefore about 1,500,000°C. The hot regions of the corona are a bit more diffuse, showing how the magnetic field spreads out once it rises in the corona.

The hottest temperatures that EIT can observe appear through its fourth filter, at 284 Å. This shows Fe XV gas, which is 3,600,000°F to 4,500,000°F (2,000,000°C to 2,500,000°C). In this filter, we see clearly that the corona is bright on only some parts of the Sun and is dark on others. Those dark regions are known as *coronal holes*. They were discovered earlier with x-ray observations. The coronal holes are regions where the Sun's magnetic field is open to space instead of looping back down. Therefore, much of the gas that leaves the Sun and reaches us on Earth comes out of these coronal holes.

The coronal holes are relatively cool compared with the active corona near them. That is one reason why they are relatively dark and don't show in the filters that show the hottest gas.

### Fun Sun Facts

A neutral atom—one with all its electrons around its nucleus—is in its basic state, which is written with a Roman numeral I. So, Fe I is neutral iron. That means that once-ionized iron is Fe II. In this way, the Roman numeral is one more than the number of electrons that have left the atom. Fe IX, therefore, has lost eight electrons.



### Sun Words

**Coronal holes** are relatively dark regions of the corona seen in x-rays or extreme ultraviolet. They represent open regions of the coronal magnetic field, from which gas can easily escape into interplanetary space.

In these regions, the corona isn't bright, so we see down to the photosphere. But the photosphere doesn't emit continuous radiation strongly at the very short wavelengths that EIT observes, so there is no strong background of radiation.

When we discussed the observations of the visible corona at eclipses, we spoke of forbidden lines. The forbidden lines come from energy levels within the ions, from which it is relatively rare for electrons to make transitions. But in the extreme ultraviolet, we see the permitted lines, the normal lines that one would expect from gas this hot.

## Fast vs. Slow

SOHO's UltraViolet Coronagraph Spectrometer studies a wide range of spectral lines in the corona. Its name shows that it not only measures the spectrum of solar photosphere, but it also can block it out, to some extent. This instrument, known as UVCS, is especially famous for having found that the solar wind comes in two types: fast and slow. The fast wind comes mainly out of coronal holes, which are often found near the Sun's poles. There, the magnetic lines of force are open to the outside. The solar wind from equatorial regions, where the magnetic field lines are looped and closed in, reaches only half that speed.

## Whizzing Ions

SOHO carries a device to measure how fast ions of various atoms move in the corona. Most of the gas in the Sun—and, therefore, most of the gas in the corona—is hydrogen, so the speed of hydrogen ions is a major concern. This device also measures other ions, such as those of oxygen. An oxygen atom is more massive than a hydrogen atom, so it moves more slowly when given the same amount of energy.

## Diagnosis

A good doctor tells what is ailing you in part by measuring certain vital statistics. By comparison, the Coronal Diagnostic Spectrometer (CDS) on SOHO measures vital statistics for the Sun. It takes spectra in four spectral bands that cover the ultraviolet and visible spectrum.

For example, CDS makes maps of the solar surface showing a wide variety of temperatures. In the ultraviolet, it studies neutral helium at 584 Å (20,000°C), oxygen V at 630 Å (250,000°C), magnesium IX (1,000,000°C), iron XVI (3,000,000°C), and magnesium X (1,500,000°C).

## Blowing in the Wind

The expansion of the solar corona is not uniform. We speak of the outflow as the solar wind, and that wind is different in different directions.

When something is the same in all directions, it is isotropic; when something differs in different directions, it is anisotropic. So measuring differences in the solar wind in different directions is called measuring its anisotropies.

To do so, the Solar Wind Anisotropies experiment, or SWAN, observes the solar wind in different directions and, of course, over the time that it has operated. It thus maps how the solar wind varies from position to position and also over time. Like all the other instruments, it has followed changes on the Sun over the solar cycle.

## SOHO Peers In

Since SOHO is in continuous sunlight, it is ideally suited for helioseismology. After all, to see a very long period, it is important to avoid nighttime! These observations involve the solar photosphere, not the corona.

## Swinging Away

GOLF on SOHO isn't a game. Rather, it is an experiment that is looking for the vibrations of the Sun as a whole as part of helioseismology. Studying the Sun as a whole is known as looking at it globally. Thus, this experiment—an acronym for Global Oscillations at Low Frequencies—is looking for global oscillations.

When a wave occurs with a long period, each wavelength comes past you very seldom. Thus, its frequency is low. GOLF on SOHO specializes in these long-period waves.

## Trapped

SOHO carries another helioseismology experiment, to search for oscillations at a wide variety of periods. This experiment is optimized to look for small velocity changes in which the Sun's surface rises and falls. We use the Doppler shift to see motions toward or away from us, so we mainly see these oscillations at the center of the Sun's disk.

The greatest American scientist of the nineteenth century was Albert Michelson. He measured the speed of light with high accuracy and teamed up with chemist Edward Morley to make high-precision observations of the speed of light in different directions. To everyone's surprise, it turned out that the light traveled at the same speed in all directions. This observation was the basis for the special theory of relativity that

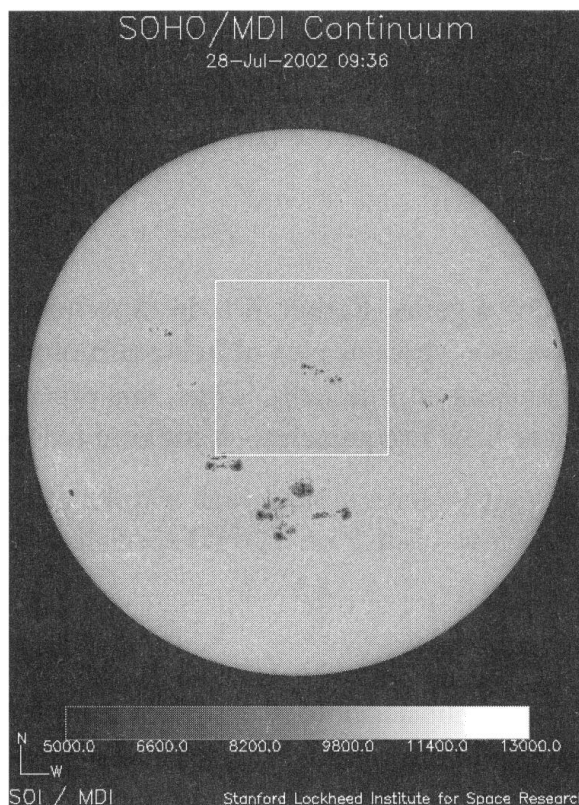
Albert Einstein invented a few decades later (though Einstein at times denied he had known of the experiment). To do his measurements, Michelson developed the technique, known as interferometry, in which light waves “interfere” with each other. That is, as they vibrate up and down, the “up” parts can add to “down” parts of another wave and cancel each other out. One of the experiments on SOHO uses Michelson’s method of interferometry to measure velocities through the Doppler shift. It is therefore called the Michelson Doppler Interferometer, or MDI.

This experiment uses its result to study helioseismology (see Color Plate 6). It is thus also named the Solar Oscillations Investigation. I don’t know why this MDI/SOI name has never been simplified.

As part of its work, MDI/SOI produces images of the solar photosphere. It is also the instrument responsible for mapping the speed of rotation of the Sun under the solar surface.

*Sunspots, as observed with the MDI/SOI instrument on SOHO. The white box shows a region that it studies in more detail.*

*(MDI/SOI Team/Stanford/Lockheed Martin/NASA/ESA)*



## Not a Virgin

Virgo is a constellation in the sky. But the VIRGO experiment on SOHO stands for Variability of solar IRradiance and Gravity Oscillations. The study of oscillations that are controlled by the Sun’s gravity is a major part of this experiment. But this experiment

also measures extremely accurately how bright the Sun is. It shows how the Sun's brightness changes over time. We discuss those VIRGO results in Part 6 of the book, where we consider further the Sun-Earth connection.

## ERNE but No Bert

As we have seen, the outflow of solar coronal gas known as the solar wind is a major part of solar astronomy. In Part 6 of this book, we discuss more about the solar wind's effects on Earth. Three of the experiments on SOHO are devoted to studying the solar wind.

One of the advantages of being at SOHO's position 1.5 million km (about 1 million miles) toward the Sun is that it can measure the solar wind as it passes, without the solar wind being much affected by Earth's magnetic field.

Three of the instruments on SOHO are devoted to measuring various quantities about the solar wind. These instruments are the Charge, ELeMent, and Isotope Analysis System (CELIAS); the COmprehensive SupraThermal and Energetic Particle analyzer (COSTEP); and the Energetic and Relativistic Nuclei and Electron experiment (ERNE). The faster a particle moves, the more energetic it is. When it gets up to be a good fraction of the speed of light, we have to use Einstein's special theory of relativity to understand its motion, and we say that its motion is relativistic.

SOHO is an example of not only international cooperation (between Europe and America), but also cosmic cooperation (between the Sun and the Earth).

A Russian-Ukrainian satellite, CORONAS-F, was launched in 2001 with several instruments that overlap SOHO's. It images the Sun in x-rays and gamma rays, measures the solar ultraviolet, and makes helioseismology observations.

## The Least You Need to Know

- ◆ SOHO has been aloft since 1995, carrying a dozen solar experiments.
- ◆ Several of SOHO experiments study coronal gas.
- ◆ One of SOHO's experiments discovered hundreds of comets.
- ◆ SOHO is ideally situated for long runs useful for helioseismology.
- ◆ SOHO is in place 1.5 million km (about 10 million miles) toward the Sun to sample the solar wind.

