Chapter 24

TRACEing Out the Loops

In This Chapter

- The Transition Region and Coronal Explorer observes fine solar details
- TRACE covers various temperature regimes from the photosphere on up through the transition region and corona
- Fine structure maps out the coronal magnetic field
- The solar surface is in turmoil

Nothing in the universe has a really sharp edge. There is always a place, however thin, between one thing and another. Just above the solar photosphere and the corona, the temperature arises within hundreds of kilometers from about 18,000°F to 1,800,000°F (10,000°C to 1,000,000°C). The space in which this change occurs is known as the *transition region.* Every photon of light and particle that moves out of the Sun must pass through this transition region, however thin and invisible it might be. The gas in the region emits interesting spectral lines in the ultraviolet. So when NASA sent up one of the small spacecraft in its Explorer series to study the solar corona, the spacecraft studied the transition region as well, as a bonus.

You'll Think You're Up Close

Decades ago, in the era of the series of Orbiting Solar Observatories, a decision was made at NASA and by solar space scientists to concentrate on extending the band of colors that could be observed. Spacecraft were made to study the ultraviolet and x-rays, with less concentration on showing details. Only recently did any solar spacecraft reveal details on the Sun with higher resolution than is available from the Earth.

Several attempts were made to provide a solar spacecraft with a relatively big telescope and high resolution. One of these was the 1980's Solar Optical Telescope (SOT). Unfortunately, its mirror was being made by the same contractor that made the mirror for the Hubble Space Telescope. When in 1990 Hubble's mirror was discovered to be flawed, the investigation and the taint killed SOT. A scaled-down successor, High Resolution Solar Observatory, also didn't make it to the launch pad. The coffee cup I have with its name on it is one of the few remainders of this ill-fated mission.

SOHO has a wide range of instruments and provides magnificent views of different layers of the solar atmosphere by using filters or coronagraph occulters. However, none of its instruments has really high resolution. Seeing the details of the solar corona had to wait still longer.

Sun Words

The **transition region** is the location between the chromosphere and the corona. There, solar gas rises in temperature from about 18,000°F to 1,800,000°F (10,000°C to 1,000,000°C).

Though no high-resolution solar satellite made it on to NASA's final plans for a major mission, several solar missions have become part of NASA's series of smaller spacecraft, called Explorers. One of them, named the Transition Region and Explorer Spacecraft, or TRACE, made it into space on an unmanned rocket in 1998.

The TRACE mission was planned and supervised by Dr. Alan Title of the Lockheed Martin Solar and Astrophysical Laboratory in California. Dr. Leon Golub of the Smithsonian Astrophysical Observatory, part of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, made the high-precision mirrors. One of the problems with observing the Sun through different filters or in different ways was aligning the instruments to perfection afterward. The TRACE mission solved that problem by using only a single telescope, but having several filters coated onto the mirror surfaces. A large rotating shutter had only one quadrant open, allowing scientists to select which filter was in use. The filter selection might change, but the image size or distortions in the image wouldn't.

TRACE was sent into an unusual orbit. It orbits Earth rather than hovering in the direction of the Sun like SOHO. It is much less expensive in terms of rocket power and price to go into such an Earth orbit. But TRACE orbits from pole to pole, instead of at a slight angle to the equator, like most spacecraft. Its orbit is always perpendicular to the direction from which the Sun is shining. This *Sun-synchronous orbit* keeps the heating constant on the telescope system and keeps the Sun continuously in view without ever having a nighttime during nine months out of every year.

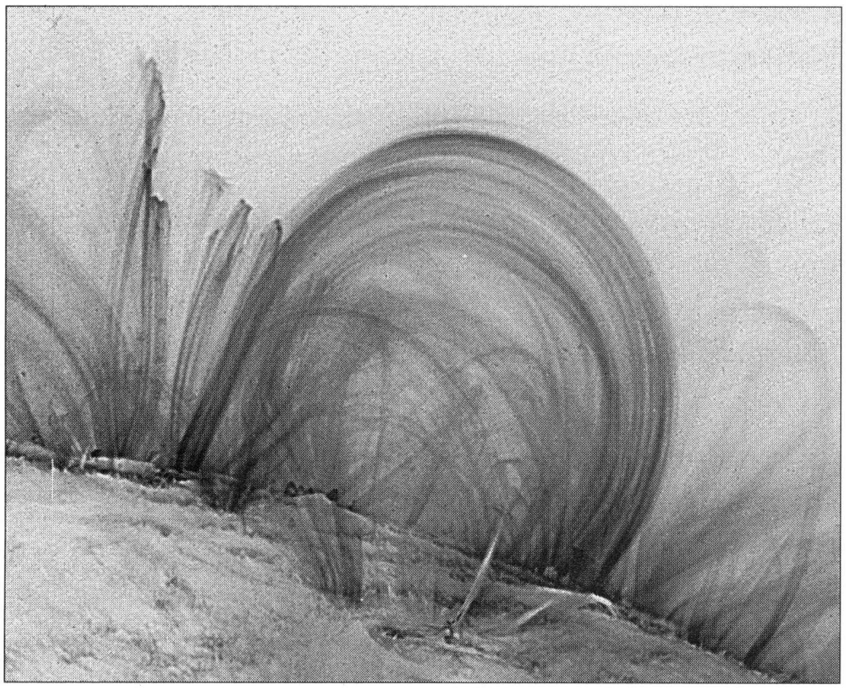
Sun Words

In a **Sun-synchronous orbit,** the spacecraft goes around the Earth every two hours or so, but always in an orbit whose plane is perpendicular to the direction toward the Sun. This puts the spacecraft in continuous view of the Sun for most of each year.

TRACE uses filters that are made of thin coats of metal deposited on the mirror surface. Even though its wavelengths are short, these filters and the telescope operate face-on into the beam rather than at grazing incidence. The multiple coatings not only provide filtering, but they also enhance the percentage of the extreme-ultraviolet light reflected.

Fun Sun Facts

Half an arc second on the Sun corresponds to a region about 400 km (250 miles) across, roughly the distance from Boston to New York.



The wonderful resolution of the TRACE spacecraft leads to beautiful images of these loops of gas seen in the extreme ultraviolet.

(Lockheed Martin Advanced Technology Center and NASA)

The 30-cm-diameter (12-inch-diameter) telescope was designed to provide pixels only half an arc second across, as good as or better than topical ground-based seeing. The mirror is of the Cassegrain design, in which light passes by a small mirror to hit the large main mirror. Then a reflection from the main mirror off the secondary mirror brings the solar beam back through a hole in the main mirror, where more filters and, ultimately, the detectors are located. The secondary mirror can move on a timescale of 1⁄10 second, in order to compensate for jitter in the spacecraft.

Ultra and Beyond

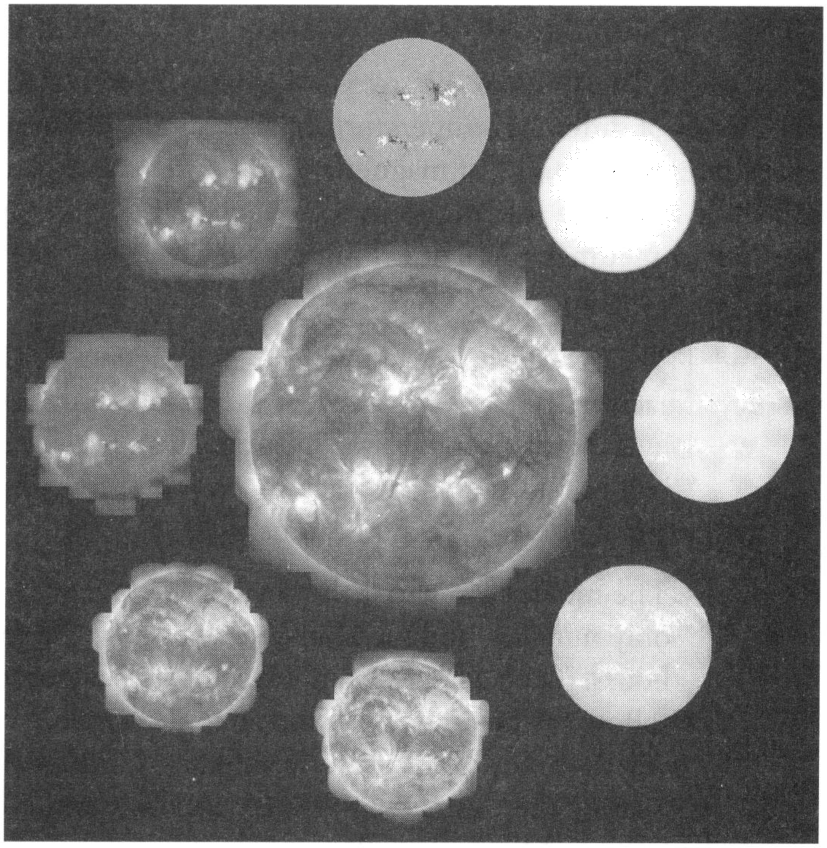
Ultraviolet technically starts beyond the purple, at the short-wavelength end of the rainbow that people can see. But the ultraviolet light observed with TRACE is only about half those wavelengths, and it approaches the limit of what people tend to say is x-rays at 100 Å. (An angstrom—Å—is a ten-billionth of a meter and is the unit astronomers usually use for visible light and shorter wavelengths. Visible light runs from about 4,000 Å at the short end of the visible to about 6,700 Å in the red.) Here are some specifics of ultraviolet wavelengths:

- **4,000 Å:** The wavelength of the ultraviolet end of the human eye's sensitivity.
- **2,500 Å:** TRACE's filter for viewing the photosphere.
- **1,700 Å:** TRACE's filter for observing the chromosphere.
- **1,570 Å:** Another TRACE filter for observing the photosphere, passing light from neutral carbon, once-ionized iron, and continuous radiation.
- **1,550 Å:** TRACE's filter for observing the transition region by studying three-times-ionized carbon.
- **1,216 Å:** The fundamental line of hydrogen known as Lyman-alpha. It originates almost entirely in the chromosphere.

And here are some of the specifics at much shorter wavelengths known as the extreme ultraviolet (EUV):

- **284 Å:** TRACE's filter for the hottest coronal gas, that of 14-times-ionized iron, which occurs at about 3,600,000°F (2,000,000°C).
- **195 Å:** TRACE's filter for observing moderately hot coronal gas, that of 11-times-ionized iron, which occurs at about 2,700,000°F (1,500,000°C). It is also useful during solar flares, since then radiation from 23-times-ionized iron (iron that has lost all but 3 of its normal quota of 26 electrons) appears in it.

- **171 Å:** TRACE's filter for observing standard coronal gas, since it is sensitive to eight-times-ionized iron, which occurs at about 1,800,000°F (1,000,000°C).



The central image is a composite of the three TRACE coronal images from June 29, 1999. The surrounding images are, clockwise starting from the top: SOHO/MDI magnetic map, white light, TRACE 1,700 Å continuum, TRACE Lyman-alpha, TRACE 171 Å, TRACE 195 Å, TRACE 284 Å, and Yohkoh x-ray image.

(Lockheed Martin Advanced Technology Center and NASA)

The Sun Is Loopy

X-ray images of increasing quality over the past decades have shown that the corona seems to be made entirely of loops of gas. That is, arches of material connect two spots on the Sun. Solar hot gas is ionized, which makes it sensitive to the magnetic field. Ionized gas moves easily and freely alongside magnetic lines of force. But ionized gas does not easily cross magnetic lines of force. So the loops that we see when we look at hot gas are presumably really loops of the magnetic field. These loops resemble the shape of the magnetic field that we saw in an earlier image (refer to Chapter 2) surrounding a bar magnet.

On the Sun, there are many magnetic regions, and the regions of positive polarity and negative polarity are often close to each other. So in addition to the Sun's overall shape of a bar magnet from pole to pole, smaller regions also have this loop structure. Indeed, solar observations have found loop structures at all scales. The TRACE observations are the finest.

In order to see such fine details, the TRACE design had to limit the field of view to only part of the Sun. TRACE sees not quite a third the Sun's diameter at a time. To make a full view of the Sun at TRACE's highest resolution, a dozen images must be grouped together as a mosaic (see page 8 of the color insert).

Viewing alternately with different filters, TRACE's excellent alignment of images reveals the arrangement of loops of different temperatures. Surprisingly, different loops come down to very different conditions of magnetic field on the solar photosphere. The footpoints of these loops are sometimes in regions that are obviously of strong magnetic field, but they sometimes come down to regions where the magnetic field is not apparent.

The Sun is very dynamic, and TRACE takes image after image at a cadence of one every few seconds. When played back at 30 frames per second, the time is compressed by a factor of approximately 100, so an hour and a half of real time plays back in a minute. Even higher factors of compression can be used.

The Solar Scoop

TRACE images can be played back as movies. Samples of the movies are available to everyone on the World Wide Web. Their large-scale reproduction in the IMAX movie *SolarMax*, accompanied by artificial sound through the many loudspeakers and subwoofers, is overwhelming and beautiful. (See vestige.lmsal.com/TRACE/POD/TRACEpod.html.)

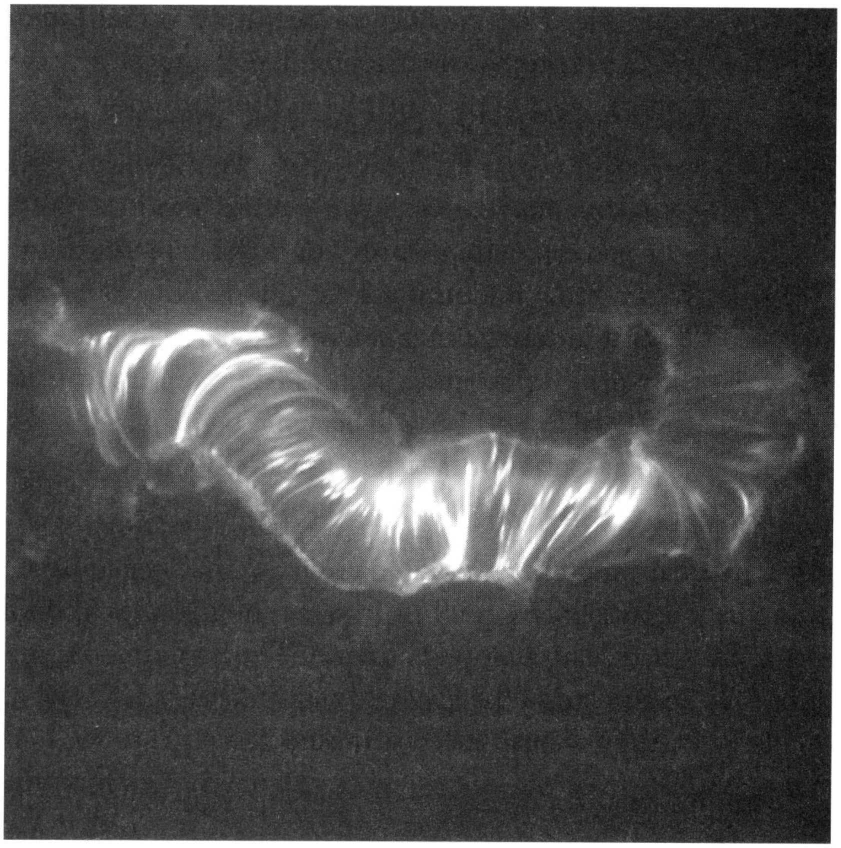
The movies show that the smaller loops may live only minutes, and medium-size ones may live for hours. They change rapidly. Scientists have tried to follow the heating of the loops, to determine whether they are perhaps heated at the top, with the heating then spreading down in seconds to the bottoms and footpoints. After all, if the corona is made entirely of loops, then the question of how the loops are heated is equivalent to the important question of how the corona is heated to its temperature of millions of degrees.

The answers to such questions depend not only on observations, but also on theoretical modeling. Theoretical modeling, in which a scientist these days uses not only equations but also usually a computer to help with calculations, depends on assumptions that are made to simplify the situation. The Sun is so very complicated, however, that simple situations are not realistic. A major problem is to figure out which simplifications in the model are okay to make and which affect the validity of the result.

One reason the TRACE spacecraft is such a valuable source of information is that the detail that it sees may be getting down to the actual size of the structure of the coronal elements on the Sun. Earlier images of the Sun from the ground and from space have blurred these features. Scientists have deduced average temperatures, densities, and other properties from these averages. But it may be that no actual features have conditions anything like the deduced average.

Solar Scribblings

Sometimes taking an average distorts the real situation. For example, if you have four people who make $20,000 per year and one who makes $2 million per year, then the five people together make $2,080,000 per year. The average amount of money made is the total divided by five, or $416,000 per year. Note that such an average is pretty misleading because neither the rich person nor the four poorer people have incomes anywhere near the average. The situation can be similar on the Sun when you take averages of coronal conditions.



At the low resolution of the past, this object would have looked like a long filament with gas flowing along it. TRACE's high resolution reveals it to be made of small loops in the perpendicular direction. TRACE's abilities can thus prevent fundamental misunderstandings.

(Lockheed Martin Advanced Technology Center and NASA)

Fire Burn and Cauldron Bubble

Macbeth's witches may not be causing the solar coronal loops to form and move around, but the motions are quite rapid and significant. The TRACE movies have shown the solar corona to be continuously active on all scales.

In particular, the loops of gas can be seen not only to move slowly around on the Sun, but also to change abruptly. If you watch a region for a while, you may well see dramatic changes in the angles at which some of the loops appear. Since the loops merely reveal the underlying loops of magnetic lines of force, we are really seeing the Sun's magnetic field and how it changes.

The magnetic field is generated below the photosphere from a dynamo process, with moving material generating a magnetic field just as it does in a General Electric dynamo that generates power for the electric lines that bring electricity to your home. This magnetic field sticks up through the photosphere, and the coronal loops show just the tops of magnetic lines of force that are kinking up and pushing through. Solar scientists have long known that the active regions are seething with motions. Such motions have shown up in long-term movies of sunspots themselves, for example. The TRACE observations reveal the cause of the motions and turmoil in a dramatic way.

In particular, the magnetic lines of force come upward from a footpoint that has one magnetic polarity and returns downward to a footpoint that has the opposite polarity. In regions in which various loops are jumbled together, a loop may join from one footpoint to another one in order to simplify the structure. Of course, it goes from a footpoint of one polarity to another of the same polarity, since its other footpoint has the opposite polarity. Such activity is called *magnetic reconnection.*

So much magnetic reconnection is happening on the solar surface at all times that we usefully think of the surface as a *magnetic carpet.* The magnetic carpet is being studied by several instruments on SOHO, whose scientists first reported it, as well as by TRACE. Some of the energy from the magnetic reconnection comes from an electric field in the loops that accompanies the changing magnetic field. A lot of energy is released as the electric fields short-circuit.

The process of magnetic reconnection can release a lot of energy. Thus, it can be a source of the heating of the corona.

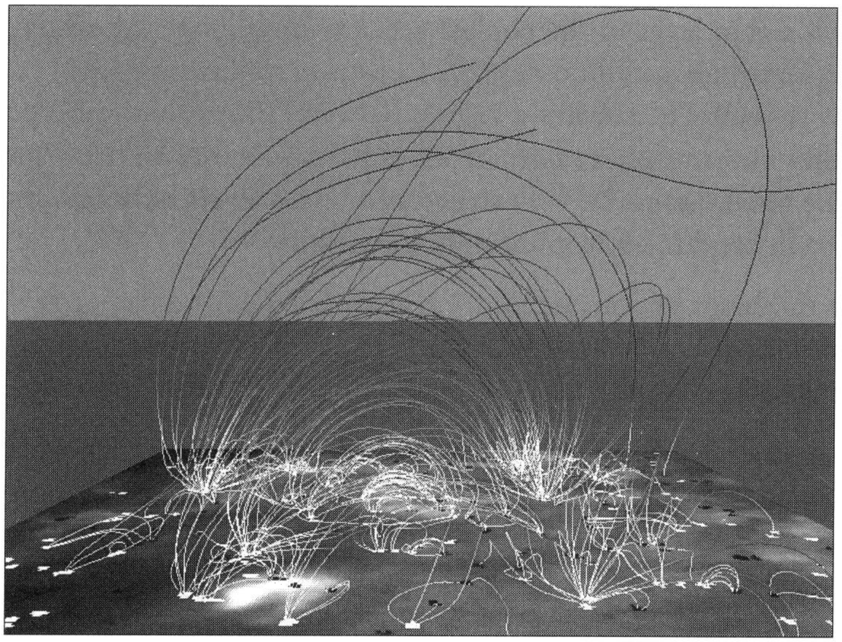
Solar Scribblings

Alan Title, head of the TRACE mission, has pointed out, "Each one of these loops carries as much energy as a large hydroelectric plant, such as the Hoover Dam, generates in about a million years!"

Sun Words

Magnetic reconnection is the abrupt change of the arrangement of loops in a region on the solar surface in order to make a lower-energy and more stable situation.

The **magnetic carpet** of the solar surface is the term that shows how common and how dynamic changes in the magnetic field are. A tangled magnetic field is found all over the images of the lower corona, and the resulting magnetic reconnection on small scales is very common.



The magnetic carpet, with the magnetic lines of force calculated and drawn in on a photograph of the solar surface. Originally, the heating was measured with the Extreme-ultraviolet Imaging Telescope on SOHO, whose image is shown, and the magnetic field was measured with SOHO's Michelson Doppler Imager.

(Lockheed Martin Advanced Technology Center and NASA)

Before it was seen to be so common, magnetic reconnection had not been expected, on theoretical grounds, to occur in the solar corona. As with so many solar phenomena, it was not predicted but had to be explained after it was found observationally. Scientists using powerful computers have now modeled the magnetic field near the solar surface in three dimensions, an advance over the simplifications introduced in the old two-dimensional calculations. The models show that convection—boiling—at the level of the photosphere brings turbulence to the lower corona. The turbulence generates electric currents that carry energy away by heating the surrounding material. Magnetic reconnection occurs during the disappearance of the currents.

The Solar Scoop

Take a virtual walk on the magnetic carpet at www.lmsal.com/magnetic.htm.

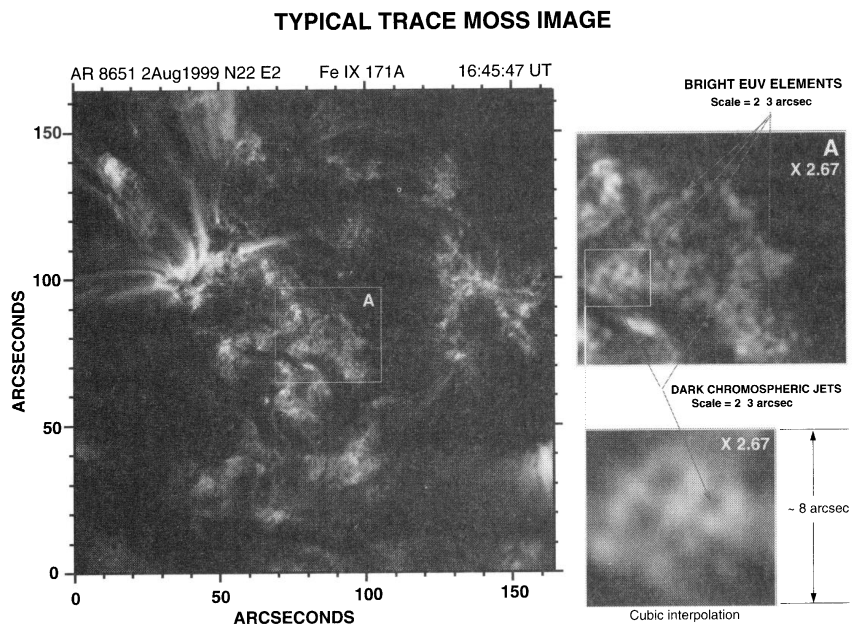
No Rolling Stones

One of the terms much discussed by some TRACE scientists is moss, a structure controversially reported in some of the images. If the old adage that "a rolling stone gathers no moss" is true, we can conclude (as we, of course, knew) that either there are no stones on the Sun or that they are rolling fast enough to leave the moss in place. Seriously, the term *moss*, as with many scientific terms, has no actual connection to its terrestrial counterpart. But on some TRACE images, the moss is seen as a low background, just as terrestrial moss on a stone may be faintly present. It appears spongy, with bright bits interspersed among darker regions. These latter regions are presumably dark because they are chromospheric gas, which doesn't emit brightly at the TRACE extreme-ultraviolet wavelengths at which the moss is best seen.

On the Sun, the moss is a thin layer of the coolest set of coronal material, which, of course, still makes it at least half a million degrees Celsius (a million degrees Fahrenheit). The moss reflects the transition region between the chromosphere and the corona. Since neither chromosphere nor corona is flat and uniform, the transition between them—and the moss—must be very structured on all levels of detail. Indeed, the moss is seen to vary in brightness from minute to minute.

The moss is seen near the bases of coronal loops. It usually lasts for a day or two in those locations. At times moss has been seen in the regions of solar flares, where it appears quickly as the postflare loops form.

Though TRACE has studied moss in detail, moss actually was seen and reported a bit earlier with a rocket-borne telescope. Ground-based images revealed the chromospheric connection, and SOHO instruments helped characterize it.



The low-level emission around the bases of the coronal loops on this TRACE image is known as moss.

(Lockheed Martin Advanced Technology Center and NASA)

The Least You Need to Know

- TRACE, the Transition Region and Coronal Explorer, orbits the Earth to study hot gas.
- TRACE's high-resolution images reveal small-scale structure that is important to understand.
- The magnetic carpet covers the Sun with a seething set of coronal loops that are often undergoing magnetic reconnection.
- A low-level background seen with TRACE is known as moss.