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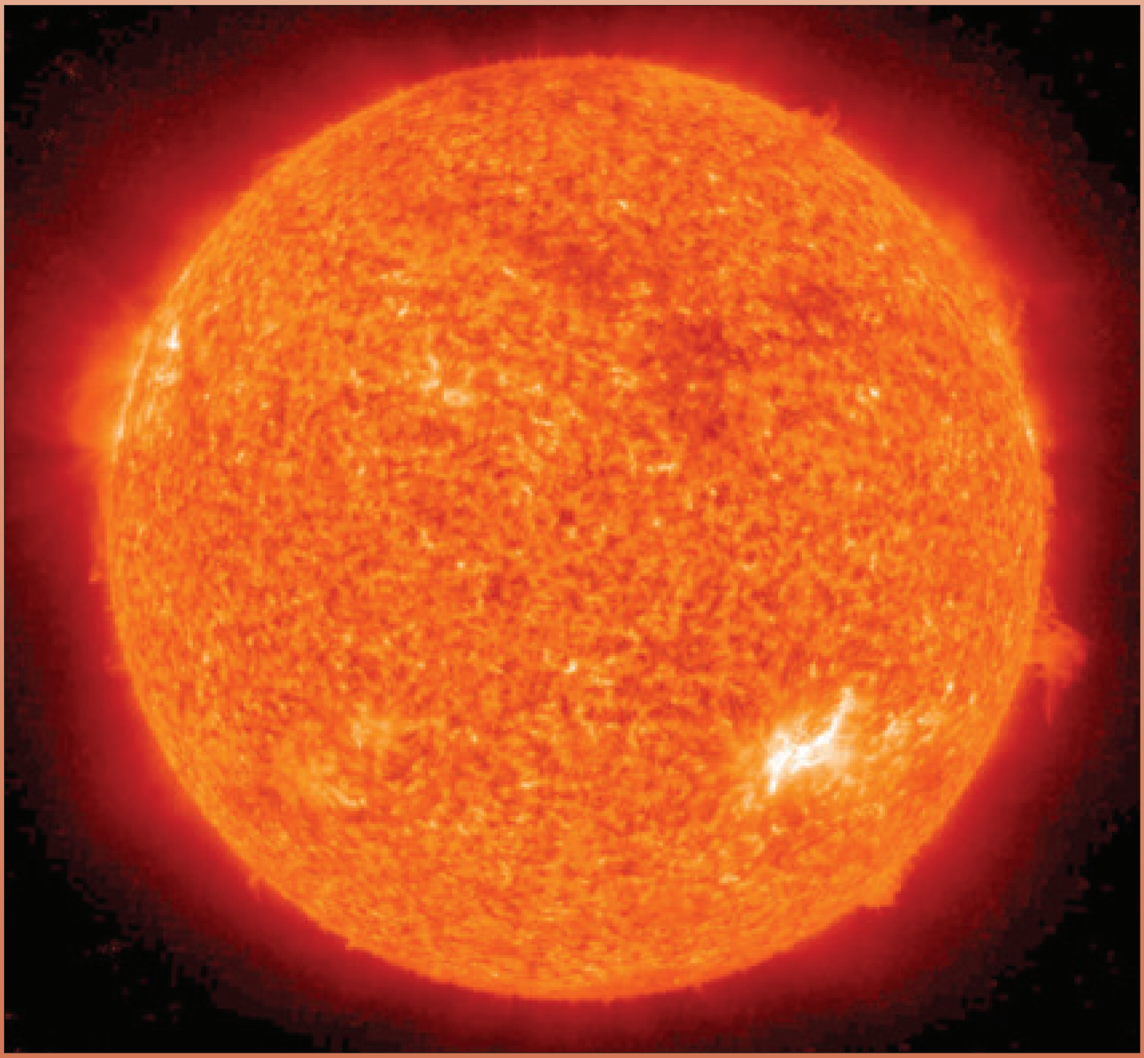


New views of the seething Sun

by Craig Covault
Contributing writer

Advances in imaging and other technologies are making waves in the solar physics community, causing a fundamental shift in the way scientists approach studies of our nearest star. New spacecraft are beginning to reveal the Sun's mysterious workings, 'seeing' for the first time the unimaginably vast scale on which its explosive blasts and other dynamic events occur.

Newly discovered events on the Sun, occurring hundreds of thousands of miles apart, are interacting to create gargantuan surface features spanning an entire solar hemisphere. These phenomena are forcing a major revision in the theories of 20th-century researchers, who did not have rapid enough imaging or sufficient spacecraft resolution to perceive that the Sun can generate interaction on such a gigantic scale.

New solar imaging satellites have now changed all that, showing for the first time that events on the Sun as far apart as the Earth and the Moon are interacting to create new features.

So big

The 870,000-mi.-diam. Sun routinely drives magnetic fields that within seconds can accelerate 200 billion lb of multimillion-degree plasma to velocities of 1 million mph. Researchers had always believed these occurred on a regional scale, not over a whole hemisphere or more.

But on August 1, 2010, three NASA and APL (Applied Physics Laboratory) spacecraft—the high-resolution Solar Dynamics Observatory (SDO) and the twin STEREO (Solar Terrestrial Relations Observatory) satellites—watched an entire hemisphere of the Sun erupt.

The eruption occurred mostly on the side facing Earth, posing a real risk to other orbiting satellites and to large electrical facilities on the ground. Facility operators and satellite controllers were ready with procedures to limit damage, but once the large coronal mass arrived at the planet it proved less dense than anticipated and therefore less of a threat.

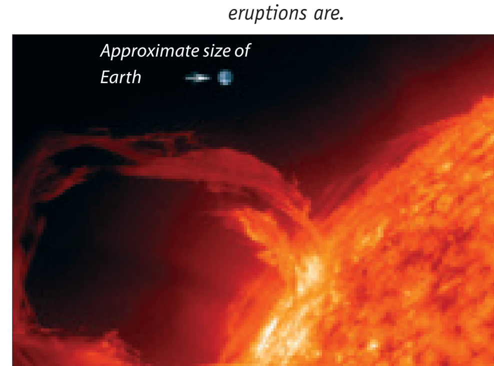
The wide-ranging eruption was documented by measurements of magnetic field lines dancing across half the Sun. Filaments of magnetism also were observed as they snapped and exploded, pushing huge shock waves across the stellar surface and blasting billion-ton clouds of hot gas into space. Astronomers knew they had witnessed something big—so big that it shattered old ideas about solar activity.

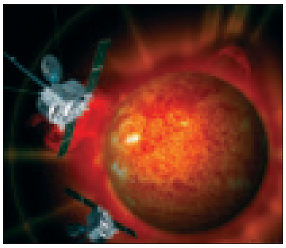
Watching the fireworks

The Sun is coming out of solar minimum, the period when solar events dwindle, quieting the star. But as the mid-2011-2014 solar maximum draws closer, solar fireworks are going to intensify. Watching them will be powerful instruments on the STEREO space-

(Opposite) A flare bursts from the Sun in this detailed image taken on August 1, 2010, by the STEREO Ahead telescope.

The Earth is superimposed on a solar eruptive prominence as seen in extreme UV light (March 30, 2010) to give a sense of how large these eruptions are.





As the two STEREO spacecraft orbit the Sun, one is far ahead of Earth and the other far behind. This enables them to cover virtually the entire solar disk simultaneously.

craft, which can capture 3D images, and SDO, a marvel of high-resolution simultaneous multiwavelength imaging in extreme ultraviolet.

SDO is one of the largest solar observing spacecraft ever placed in orbit. The satellite's solar panels are 21.3 ft wide; its total mass during its February 2010 launch on an Atlas V was 6,800 lb.

The SDO telescopes can take images every 0.75 sec. The resulting data are having the same transformative effect on solar physics that the invention of high-speed photography had on many sciences in the 19th century, says a NASA Goddard SDO engineer. And SDO does not stop at the stellar surface. A sensor on the observatory can actually look inside the Sun at the solar dynamo itself—the source of solar activity.

Imagine watching an IMAX movie that never stops. The enormous screen in effect stars a star. The new trio of spacecraft have the primary mission of helping to improve space weather forecasting—a growing scientific field affecting military and civil spacecraft operations and hundreds of other Earth-based operations that involve electrical and magnetic energy. But the Sun is also a star, and watching it much more closely yields tremendous data about what is happening on the surface of every distant pinpoint of light in the night sky going back millions and billions of light-years.

Voluminous yield

The volume of images and data that SDO can feed onto the IMAX screen is equivalent to downloading half a million I-Tunes each day. By some estimates, SDO will transmit 50 times more science data than any mission in NASA history.

Its images all have 10 times greater resolution than high-definition television. And because such fast imaging cadences have never before been attempted by an orbiting observatory, the potential for discovery is great. The data rate is equally great.

To handle the load, NASA has built two 60-ft SDO antennas near Las Cruces, New Mexico. SDO's geosynchronous orbit will keep the observatory in constant view of the antennas around the clock for the duration of the observatory's 5-10-year lifespan.

Spectacular images have been acquired by SDO's three instruments:

• The Extreme Ultraviolet Variability Experiment will measure changes in the Sun's ultraviolet output. Extreme UV (EUV) radiation from the Sun has a direct and powerful effect on Earth's upper atmosphere, heating it, puffing it up, and breaking apart atoms and molecules.

• The Helioseismic and Magnetic Imager will map solar surface magnetic fields and peer beneath the Sun's opaque surface using a technique called helioseismology. A key goal of this experiment is to decipher the physics of the Sun's magnetic dynamo, which in pictures resembles the circular splash of a rock thrown into a pond.

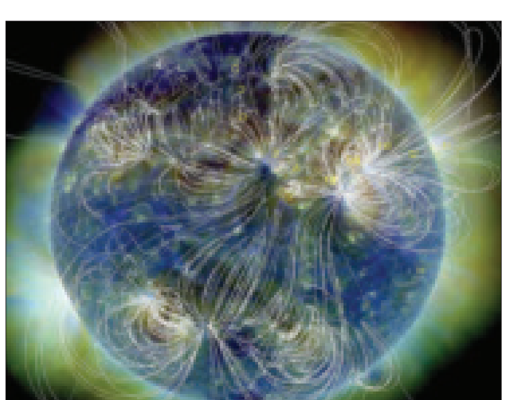
• The Atmospheric Imaging Assembly, or AIA, is a battery of four telescopes designed to photograph the Sun's surface and atmosphere in 10 different wavelengths, or colors, selected to reveal key aspects of solar activity. Each telescope supports two separately coated halves of both the primary and secondary mirrors. The mirrors, in combination with front and back filters, and in one telescope a mechanical selector, provide access to 10 distinct wavelength intervals. These range from a broadband visible channel and two UV channels to seven channels in the extreme ultraviolet.

Seeing in STEREO

During the solar cataclysm, researchers were watching with the seven SDO EUV channels taking images every 12 sec.

Although SDO is extremely high resolution, the orbits of the twin STEREO spacecraft provide spacing between the Earth and Sun to give coverage of nearly two solar hemispheres simultaneously. This offered the first ever opportunity to see back around the solar disk to discern the size of the event—and the scale of what was happening astonished everyone watching.

When the twin satellites were launched in 2006, one spacecraft was maneuvered well forward of Earth and the other parked well behind to watch much larger areas of the Sun simultaneously. The two spacecraft weigh 1,364 lb each and were launched



After the August 2010 eruption, a second major eruption showing magnetic field lines dancing across the Sun's front side was measured using graphics. Filaments of magnetism snapped and exploded, shock waves raced across the stellar surface, as billion-ton clouds of hot gas billowed into space.

one atop the other on an Atlas V. The mission's total cost is about $550 million, while SDO cost about $850 million.

STEREO's specialty is to image coronal mass ejections (CMEs) blown off the Sun by big solar flares—explosions within the surface plasma. A CME is a giant blast of solar material with a mass of billions of tons.

There are 16 instruments per STEREO spacecraft. Both satellites, by imaging CMEs in 3D, have the same objectives: to understand the causes and mechanisms of CME initiation and characterize their propagation; and to discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium. They also aim to improve determination of the structure of the ambient solar wind.

CMEs, storms, and magnetic mayhem

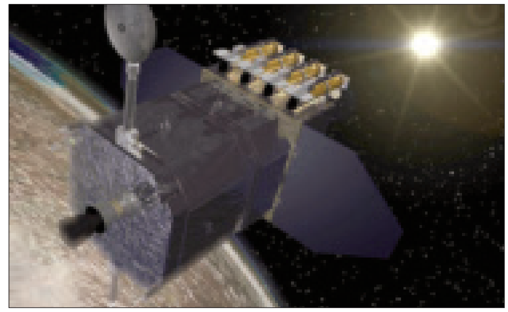
CMEs are the most energetic of solar explosions, ejecting up to 200 billion lb of multimillion-degree plasma into interplanetary space, at departure velocities of up to 1,000 mi./sec. They often look like bubbles and, when seen close to the Sun, can appear bigger than the Sun itself, though their density is extremely low.

In contrast to the steady-state solar wind, CMEs originate in regions where the magnetic field is closed. They result from the catastrophic disruption of large-scale magnetic structures such as coronal streamers. CMEs can occur at any time during the solar cycle, but they increase in daily frequency from about 0.5 during the solar minimum to about 2.5 daily during the solar maximum, which the Sun is entering.

Fast CMEs—those that outpace the ambient solar wind—give rise to large geomagnetic storms when they encounter Earth's magnetosphere. These storms can disrupt power grids, damage satellite systems, and threaten astronauts. They can result from the passage of the CME itself or the shock created by the fast CME's interaction with the slower moving solar wind.

"The August 1st event really opened our eyes," says Karel Schrijver of Lockheed Martin's Solar and Astrophysics Lab in Palo Alto, California. "We see that solar storms can be global events, playing out on scales we scarcely imagined before."

For the past several months, Schrijver has been working with fellow solar physicist Alan Title to understand what happened during what they call 'the Great Eruption,' an event likely to appear in science textbooks for decades.



Equipped with the most powerful civilian data system ever flown, the $850-million SDO is studying the solar atmosphere on small scales of space and time and in numerous wavelengths simultaneously. It is the highest resolution solar spacecraft ever launched.

"To predict eruptions we can no longer focus on the magnetic fields of isolated active regions; we have to know the surface magnetic field of practically the entire Sun," Title told the fall 2010 meeting of the American Geophysical Union (AGU).

August 1—the Great Eruption

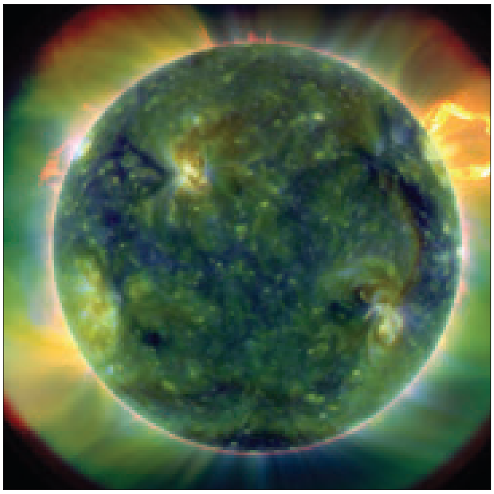
Tony Phillips, another solar researcher for NASA, described the importance of the observations and the sequence of events. The new data show that "explosions on the Sun are not localized or isolated events; instead, solar activity is interconnected by magnetism over breathtaking distances. Solar flares, tsunamis, coronal mass ejections—they can go off all at once, hundreds of thousands of miles apart, in a dizzyingly complex concert of mayhem," said Phillips in his NASA blog.

This revelation increases the workload for space weather forecasters, but it also improves the potential accuracy of their predictions.

"The whole-Sun approach could lead to breakthroughs in predicting solar activity," says Rodney Viereck of NOAA's Space Weather Prediction Center in Boulder, Colorado. "This in turn would provide improved forecasts to our customers, such as electric power grid operators and commercial airlines, who could take action to protect their systems and ensure the safety of passengers and crew."

In a paper they prepared for the *Journal of Geophysical Research* (JGR), Schrijver and Title broke down the Great Eruption into more than a dozen significant shock waves, flares, filament eruptions, and CMEs spanning 180 deg of solar longitude and 28 hr of time. It seemed to be a cacophony of disorder—until they plotted the events on a map of the Sun's magnetic field.

The events involved a lot of what solar physicists call a 'separatrix,' a magnetic fault zone where small changes in surrounding plasma currents can set off big electromagnetic storms.



In this full-disk, multiwavelength EUV image of the Sun taken by SDO on March 30, 2010, false colors trace different gas temperatures. Reds are relatively cool at about 107,540 F; blues and greens are hotter, greater than 1,799,540 F.

Title describes the 'Eureka!' moment: "We discovered that all the events of substantial coronal activity were connected by a wide-ranging system of separatrices, separators, and quasiseparatrix layers."

Phillips says that researchers have long suspected this kind of magnetic connection was possible. "The notion of 'sympathetic' flares goes back at least three quarters of a century," according to what Schrij-ver and Title wrote in their JGR paper. Sometimes observers would see flares going off one after another, like popcorn, but it was impossible to prove a link between them. Arguments in favor of cause and effect were statistical, and frequently full of uncertainty.

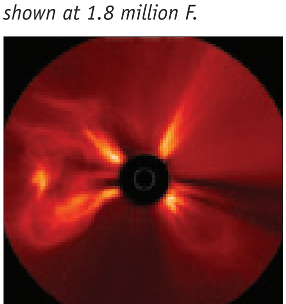
Says Lika Guhathakurta, NASA's Living with a Star program scientist, "For this kind of work, SDO and STEREO are game-changers. Together, the three spacecraft monitor 97% of the Sun, which allows researchers to see connections that they could only guess at in the past."

To wit, barely two-thirds of the August event was visible from Earth, yet all of it could be seen by the SDO-STEREO team. Moreover, SDO's measurements of the magnetic field revealed direct connections between the various components of the Great Eruption—no statistics required.

Much remains to be done. "We're still sorting out cause and effect," says Schrijver. "Was the event one big chain reaction, in which one eruption triggered another—bang, bang, bang—in sequence? Or did everything go off together as a consequence of some greater change in the Sun's global magnetic field?"

Further analysis may yet reveal the underlying trigger; for now, team members are still wrapping their minds around the global character of solar activity. "Not all eruptions are going to be global," notes Guhathakurta. "But the global character of solar activity can no longer be ignored."

The occulting disk on SDO blocks the bright solar surface to observe fine detail in a CME. These result from explosions caused by magnetic stress in the Sun's atmosphere, which is shown at 1.8 million F.



Another mystery

SDO is also helping to solve the great mystery of why the Sun's outer atmosphere, the corona, is a million degrees hotter than the surface, the photosphere.

"Among the many constantly moving, appearing, disappearing, and generally explosive events in the Sun's atmosphere, there exist giant plumes of gas—as wide as a state and as long as Earth—that zoom up from the Sun's surface at 150,000 mph. Known as spicules, these are among several phenomena known to transfer energy and heat throughout the Sun's magnetic atmosphere, or corona," says Karen C. Fox, who often writes on solar physics at NASA Goddard.

Thanks to SDO and the Japanese satellite Hinode, these spicules have recently been imaged and measured better than ever before. The imagery shows that they contain hotter gas than previously observed and thus may play a key role in helping to heat the Sun's corona to a staggering million degrees or more—a number made more surprising because the Sun's surface itself is only about 10,000 F.

"The traditional view is that all heating happens higher up in the corona," says solar physicist Dean Pesnell, SDO's project scientist at Goddard. "The suggestion is that cool gas is ejected from the Sun's surface in spicules and gets heated on its way to the corona. This doesn't mean the old view has been completely overturned, but this is a strong suggestion that part of the spicule material gets heated to very high temperatures and provides some coronal heating," Pesnell says.

Spicules were first named in the 1940s, but were hard to study in detail until recently, says Bart De Pontieu of Lockheed Martin's Solar and Astrophysics Laboratory in Palo Alto, California.

In visible light, spicules are seen to send large masses of so-called plasma—the electromagnetic gas that surrounds the Sun—up through the lower solar atmosphere or photosphere. The amount of material sent up is stunning, some 100 times as much as streams away from the Sun in the solar wind toward the edges of the solar system. But nobody knew if the spicules contained hot gas.

"Heating of spicules to the necessary hot temperatures had never been observed, so their role in coronal heating had been dismissed as unlikely," says De Pontieu.

Now, De Pontieu's team—which included researchers at Lockheed Martin, the High Altitude Observatory of the National Center for Atmospheric Research (NCAR) in Colorado, and the University of Oslo—was able to combine images from SDO and Hinode to produce a more complete picture of the gas inside these gigantic fountains.

Tracking the movement and temperature of spicules relies on successfully identifying the same phenomenon in all of the images. One complication is that different instruments 'see' gas at different temperatures. Pictures from Hinode in the visible light range, for example, show only cool gas, while those that record UV light show gas that is up to several million degrees.

To show that the previously known cool gas in a spicule lies side by side with some very hot gas requires showing that the hot and cold gas in separate images are located in the same space. Each spacecraft offered specific advantages to help confirm that one was seeing the same event in multiple images.

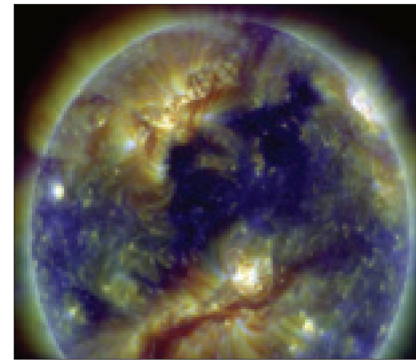
In 2009, scientists used observations from Hinode and telescopes on Earth to identify, for the first time, a spicule when looking at it head-on. (Imagine how difficult it is to determine, from over 90 million mi. away, that you are looking at a fountain when you have only a top-down view instead of a side view.) The top-down view of a spicule ensures an image with less extraneous solar material between the camera and the fountain, thus increasing confidence that any hotter gases observed are indeed part of the spicule itself.

The second aid to tracking a single spicule is SDO's ability to capture an image of the Sun every 12 sec. "You can track things from one image to the next and know you're looking at the same thing in a different spot," says Pesnell. "If you had an image only every 12 min, you couldn't be sure that what you're looking at is the same event, since you didn't watch its whole history."

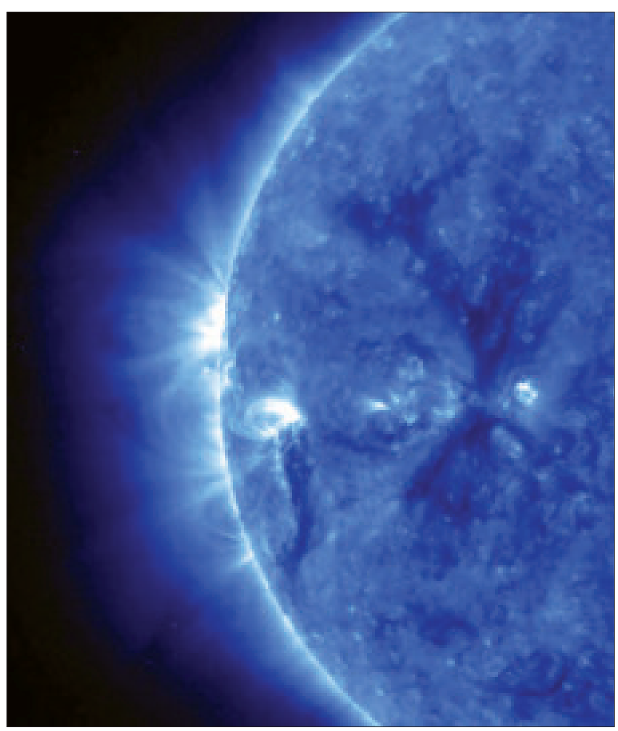
Bringing these tools together, scientists could compare simultaneous images in SDO and Hinode to create a much more complete image of spicules.

They found that much of the gas is heated to 100,000 F, while a small fraction of it is heated to millions of degrees. Time-lapsed images show that this hot material spews high up into the corona, with much of it falling back down toward the surface of the Sun. However, the small fraction of the gas that is heated to millions of degrees does not immediately return to the surface. "Given the large number of spicules on the Sun, and the amount of material in them, if even some of that superhot plasma stays aloft it would make a fair contribution to coronal heating," says Scott McIntosh from NCAR, who is part of the research team.

Of course, De Pontieu cautions that the team's results do not yet solve the coronal heating mystery. But, he says, they do challenge theorists to incorporate the possibility that some coronal heating occurs at lower heights in the solar atmosphere. De Pontieu's next step is to help figure out how great a role spicules play by studying how they form, how they move so quickly, how they get heated to such high temperatures in a short time, and how much mass stays up in the corona.



On August 1, 2010, the entire Earth-facing side of the Sun erupted in tumult. There was a powerful solar flare (white area upper left), a solar tsunami (center left), and multiple filaments of magnetism lifting off the stellar surface at lower left, large-scale shaking of the solar corona, radio bursts, a coronal mass ejection and more. Hemisphere wide violence was also imaged at far right. This multi-wavelength EUV snapshot from SDO depicts different colors for different temperatures from 1-2 million F.



Loops of highly charged particles shoot out from the Sun, as seen in extreme ultraviolet wavelengths by the STEREO spacecraft. Blue color is used to indicate temperatures in the corona of about 1,800,000 F.

Fox notes that astrophysicist Jonathan Certain, the U.S. project scientist for Hinode at NASA Marshall, says incorporating such new information helps address an important question that reaches far beyond the Sun. "This breakthrough in our understanding of the mechanisms which transfer energy from the solar photosphere to the corona addresses one of the most compelling questions in stellar astrophysics: 'How is the atmosphere of a star heated?' This is a truly fantastic discovery," says Certain.