Opening a new window on the SUN

With three instruments operating 24/7, the Solar Dynamics Observatory is gleaning new insights into how magnetic fields control solar activity. by W. Dean Pesnell

Pat Corkery/United Launch Alliance

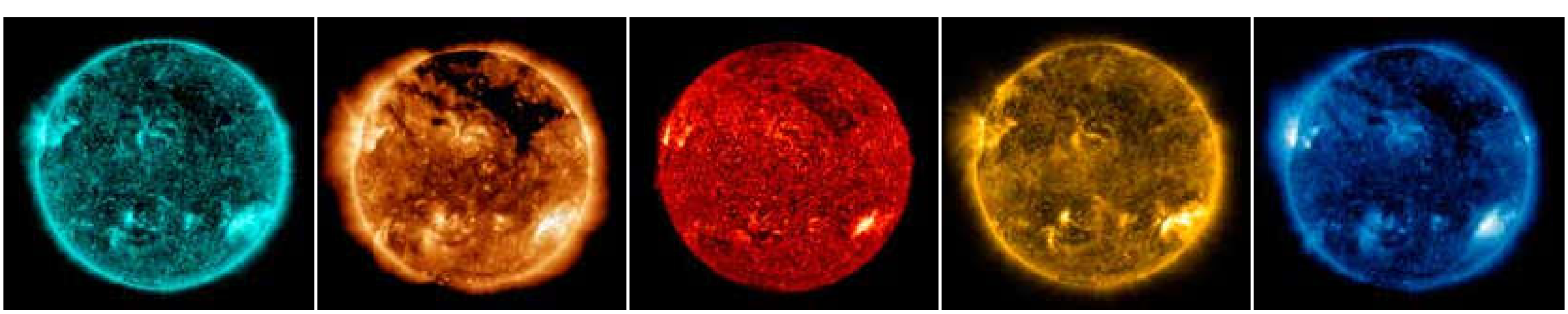
The Solar Dynamics Observatory launches from Cape Canaveral February 11, 2010, atop an Atlas V rocket with a Centaur upper stage.

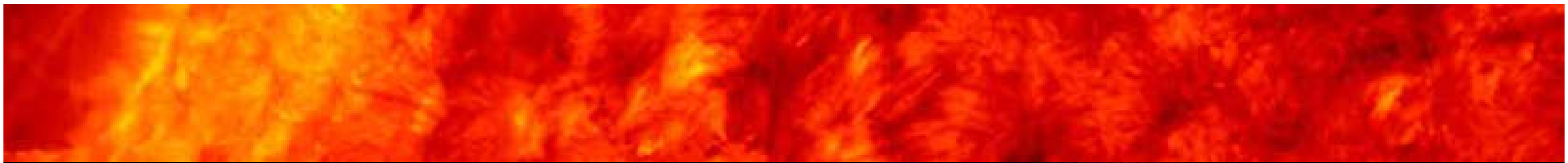
After a year in orbit, NASA's Solar Dynamics Observatory (SDO) has started to fulfill its promise. The mission's task: to examine the Sun in such detail that astronomers will be able to understand how our star's magnetic field drives solar prominences, flares, coronal mass ejections (CMEs), and other solar activity. And, just as important, the observatory will measure the changes in the Sun that cause space weather, whose effects range from power outages and navigation problems on Earth to creating drag on satellites in orbit.

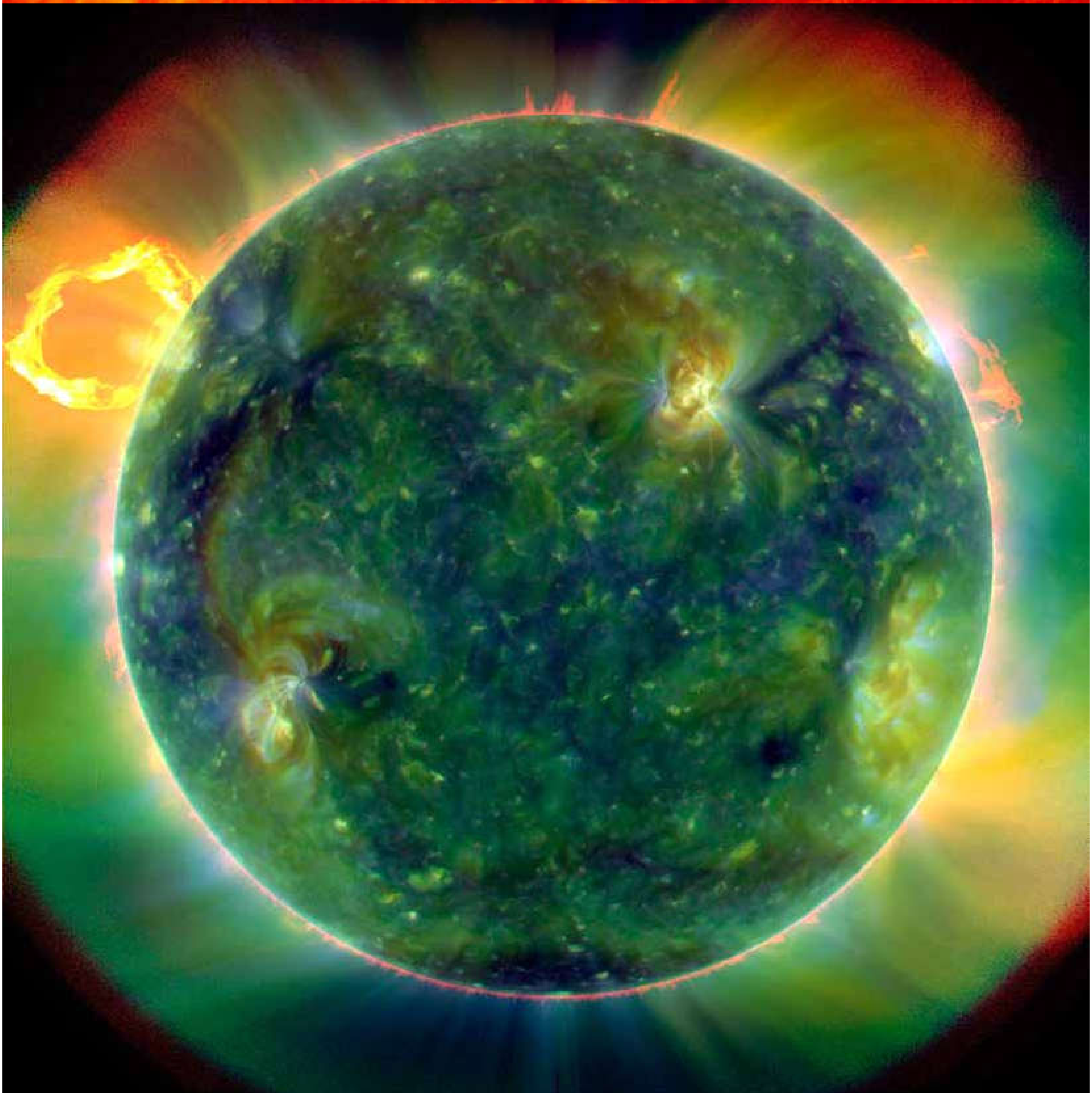
SDO began its mission February 11, 2010. That day, an Atlas V rocket roared to life on Space Launch Complex-41 at Cape Canaveral, Florida, and lofted the observatory into Earth orbit. Although the launch went smoothly, as SDO traversed the surrounding atmosphere, it demonstrated how the observatory could affect observations of solar phenomena.

A large winter storm over the eastern United States the previous day brought cold temperatures to central Florida. Coupled with a thin layer of cirrus clouds, the chill produced a sundog — a rainbow-colored patch of light 22° from the Sun. A sundog arises when sunlight refracts through six-sided ice crystals all aligned with their broad sides down.

As SDO climbed through the cirrus cloud deck, a sound wave emanating from the rocket caused the sundog to disappear. Apparently, the wave either evaporated the ice crystals or destroyed

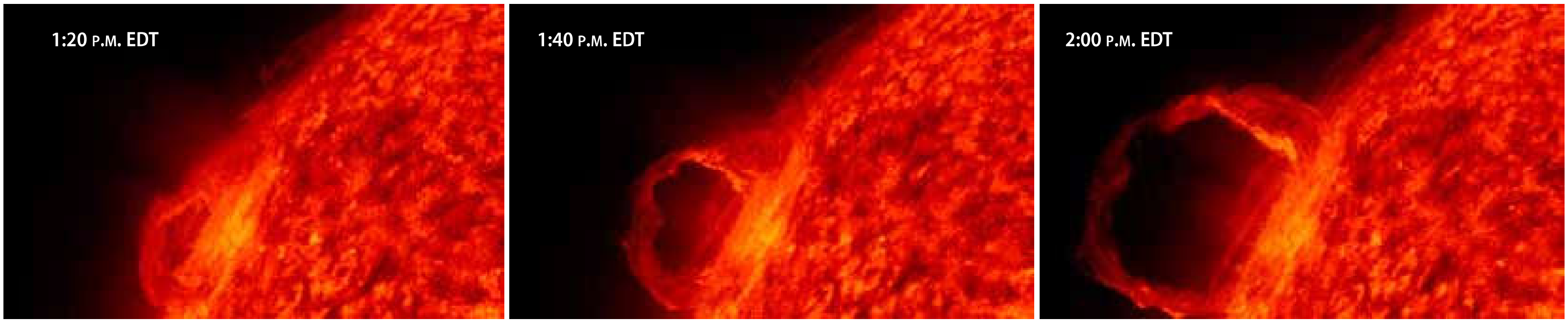






◄ **These colorful Suns** show our star's appearance July 28, 2010, at five wavelengths in the extreme ultraviolet portion of the electromagnetic spectrum. By observing the Sun at different high-energy wavelengths, solar scientists will learn how the Sun converts energy in its magnetic fields into the heat that drives solar flares. NASA/SDO/AIA Science Team

▲ **A massive solar prominence** (upper left) erupts from the Sun March 30, 2010. Scientists created this false-color, multiwavelength image with data from the Solar Dynamics Observatory. The orange-red background images on this page show the Sun's chromosphere that same day in the light of ionized helium (a wavelength of 30.4 nanometers). NASA/SDO/AIA Science Team



On March 30, 2010, a large prominence erupted on the Sun's limb and spewed hot gas into space at speeds of approximately 435 miles per second (700 km/sec). This sequence of six images from the Solar Dynamics Observatory shows the eruption lasted only a couple of hours. The observatory captured these images in the light of singly ionized helium (a wavelength of 30.4 nanometers). NASA/SDO/AIA Science Team

their matching orientations. So, within minutes of launch, SDO already had impacted solar observations. But the real proof of the mission's significance would come only when the observatory began viewing the Sun in earnest from its perch far above Earth's atmosphere.

SDO's three-pronged attack

The Solar Dynamics Observatory uses three instruments to study the Sun's magnetic field. Scientists designed these tools to probe the Sun from below its surface out to the hot corona. Their goal: to find how the magnetic field changes over time.

Scientists at Stanford University and the Lockheed Martin Space Astrophysics Laboratory (LMSAL) developed the Helioseismic and Magnetic Imager (HMI). It studies the behavior of the motions of the Sun's surface and also the magnetic fields there. The Sun is a combination of gas and its extremely hot, and thus ionized, counterpart known as plasma; its "surface" (or photosphere) is the region from which light escapes into space. Every 45 seconds, HMI makes maps of both velocities (the motions) and "line-of-sight" magnetic fields at the solar surface. It also maps the so-called vector magnetic field, the component directed across our line of sight, every 15 minutes.

The instrument makes these maps with polarizing filters that measure how the velocity and magnetic field change. To gauge velocity, they measure the Doppler shift — the change in wavelength as the distance between the Sun and SDO varies. As the solar surface enlarges, and thus moves toward SDO, the wavelength decreases; as the solar surface shrinks, the wavelength increases.

Astronomers track these changes by observing one particular spectral line over time — in this case, iron at 617.3 nanometers — and seeing how its incoming wavelength changes. The velocity maps essentially build ultrasounds of the Sun that reveal what is going on below its surface. Scientists use the same spectral line to chart the behavior of magnetic fields at the surface.

As soon as the detectors reached operating temperature, the Sun put on a show.

Space-weather forecasters use the line-of-sight maps to anticipate solar flares and CMEs. The vector-field maps, meanwhile, show the strength and direction of the magnetic field as it emerges through the surface. Although the vector field offers more information, the line-of-sight measurements are easier to produce.

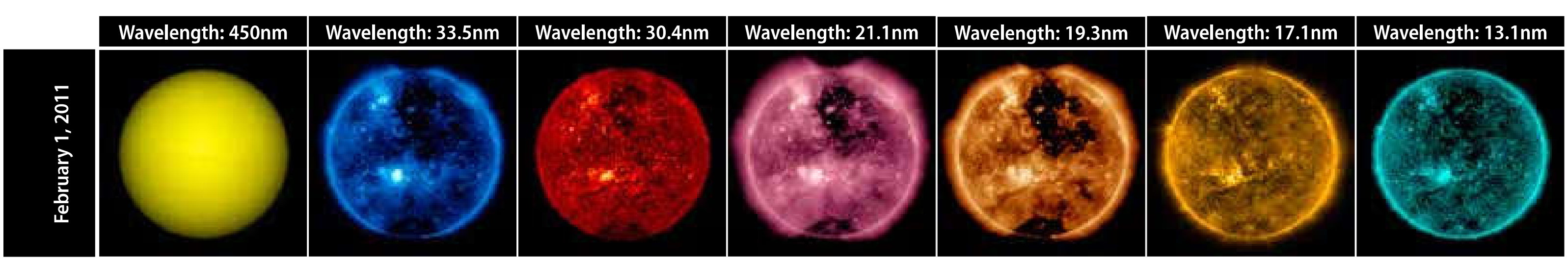
SDO's second instrument is the Extreme ultraviolet Variability Experiment (EVE). Developed at the University of Colorado's Laboratory for Atmospheric and Space Physics and the University of Southern California, EVE has three spectrographs that measure the solar spectral irradiance — the amount of energy the Sun emits at a given wavelength— for wavelengths between 0.1nm and 105nm.

EVE also includes a small X-ray imager. Extreme ultraviolet radiation from the Sun heats and ionizes the upper parts of Earth's atmosphere to such a degree that scientists call it the "heartbeat of space weather."

The third instrument aboard SDO is the Atmospheric Imaging Assembly (AIA), which scientists at LMSAL also developed. It studies how the solar corona responds to the magnetic fields that HMI observes near the Sun's surface.

AIA's four telescopes focus light onto four CCD cameras and take images of the Sun's atmosphere at 10 wavelengths: one in visible light, two in the ultraviolet part

W. Dean Pesnell *is the project scientist for NASA's Solar Dynamics Observatory.*



The Sun's character changes when viewed at different wavelengths. In visible light (far left), its photosphere typically reveals sunspots. But at shorter wavelengths in the extreme ultraviolet, the Sun's outer atmosphere (its chromosphere and corona) come into view. NASA/SDO/AIA Science Team

of the spectrum, and seven in the extreme ultraviolet part that corresponds to the ionization states of iron and helium. Data from the iron spectral lines allow SDO scientists to map the corona's temperature from 0.6 to 20 million kelvins; the helium observations probe temperatures from 30,000 to 100,000 K.

Because EVE and AIA fly together, solar astronomers can associate most changes in the Sun's irradiance with specific events, such as flares, simply by aligning changes in EVE's measurements with changes in the AIA images. This helps EVE scientists explain where their changes came from and helps calibrate AIA by determining the energy of each event.

A grand first show

After its launch, SDO took more than a month to reach its operating position. On March 16, 2010, the observatory reached its final geosynchronous orbit, in which it hovers above the longitude of its White Sands, New Mexico, receiving station. From this location, it can both observe the Sun and communicate with the ground 24 hours a day.

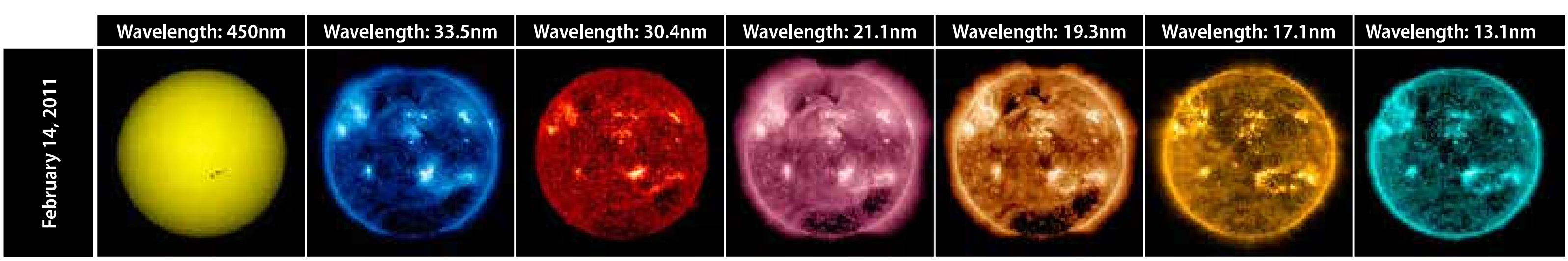
Soon afterward, NASA engineers started to turn on the electronics for each SDO instrument before cooling down the CCDs and opening the instrument doors. HMI went first and then EVE, while AIA kept its heaters on until its doors opened.

As soon as the detectors reached operating temperature, the Sun put on a show. HMI even saw a sunspot before the instrument's door fully opened. Almost immediately after the EVE doors opened at 2:43 P.M. EDT March 26, active region 11057 provided fireworks. The hot spot fired off four relatively small flares starting at 5:08 P.M. EDT.

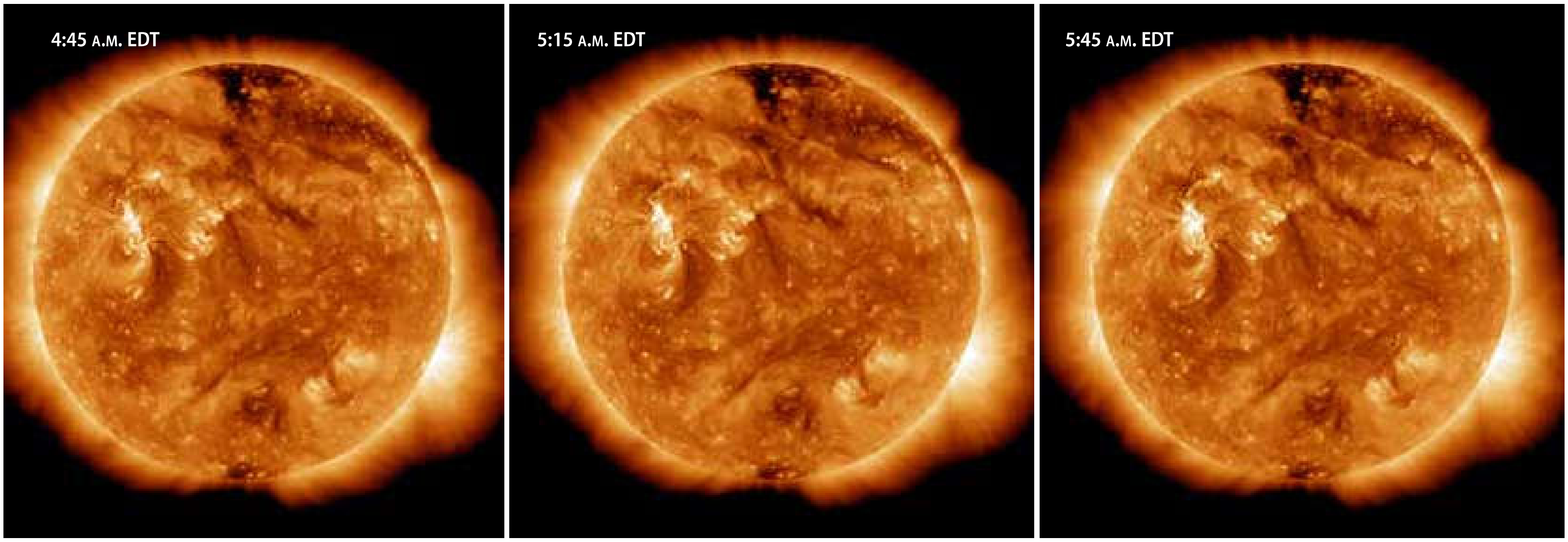
But the Sun saved its best for last. Although AIA scientists opened their doors March 27, they kept their CCDs hot to drive off contaminants. On March 30, just after the CCDs reached their operating temperatures of –94° Fahrenheit (–70° Celsius), an enormous prominence erupted off the Sun's limb. (See the sequence of images above and the large photo on page 25.)

The images show that the ring-shaped prominence sent a pulse of plasma rushing away from the Sun at a speed of about 435 miles per second (700 km/s). Before the eruption, this prominence was a long tube of magnetically contained material just above the visible surface. Then, by some still poorly understood mechanisms, it destabilized and created a small

A double rainbow arcs above one of the 18-meter radio dishes at NASA's White Sands Complex in New Mexico. Because the Solar Dynamics Observatory lies in geosynchronous orbit, the antennas here can receive all of the observatory's data. NASA/Tim Gregor



A Valentine's Day solar flare erupted from a sunspot group located just to the lower right of the Sun's center. The group shows up nicely in visible light (far left). At shorter wavelengths, the flare's brightness dominates. This February 14 event was the Sun's largest flare in more than 4 years. NASA/SDO/AIA Science Team



Active region 11092 **(the bright maelstrom halfway to the limb in the 10 o'clock direction) flared several times August 1, 2010, but that was just the start. Shock waves raced across the solar surface, disrupting the dark filaments visible above the Sun's center. At about 4:40 A.M. EDT, one of these filaments launched a coronal mass ejection toward Earth. These images show gas glowing at 1.5 million kelvins (a wavelength of 19.3nm).** NASA/SDO/AIA Science Team

CME. It is vitally important to understand these mechanisms because they produce all CMEs, which can launch up to 10 billion tons of plasma into the solar system and cause serious consequences for any object, natural or man-made, that happens to be in the way.

Since the first observations made through the AIA 30.4nm channel, SDO scientists have observed new dynamics in how coronal filaments evolve. SDO teams have studied why and how filaments form, erupt off the surface, twist, and either eject into the solar wind or return to the lower solar atmosphere as coronal "rain." Much of what solar scientists see, they don't yet understand. For example, why do some filaments escape and others have their plasma drain back onto the Sun? Are the filaments twisted when they become unstable, and do they twist more as they erupt? Does the filament heat or cool as it erupts? And how does the coronal rain interact with the dense atmosphere once it falls back to the surface?

The what and how of flares

People have watched solar flares for more than 150 years. (English astronomer Richard Carrington spotted the first September 1, 1859.) During that time, researchers have learned that flares release enormous amounts of energy by converting the Sun's magnetic energy into heat. Solar physicists classify flares as B, C, M, or X (from low- to high-energy X-rays); they also use flares' appearances in Hydrogen-alpha images to categorize them. SDO provides the additional ability to classify flares by their total energy (by combining AIA and EVE measurements) and by their development at many temperatures.

The new observatory has started to give researchers a unique look at flare evolution. Much of this is because SDO takes fresh images of the Sun almost continuously (AIA, for example, snaps eight full-disk images every 12 seconds and operates nearly 24/7). But SDO also covers a broad range of temperatures, and scientists can coordinate the measurements made through its three instruments. The Sun has produced flares of all classes for SDO, including the strongest X-class flare in more than 4 years on February 14, 2011.

SDO takes fresh images of the Sun almost continuously.

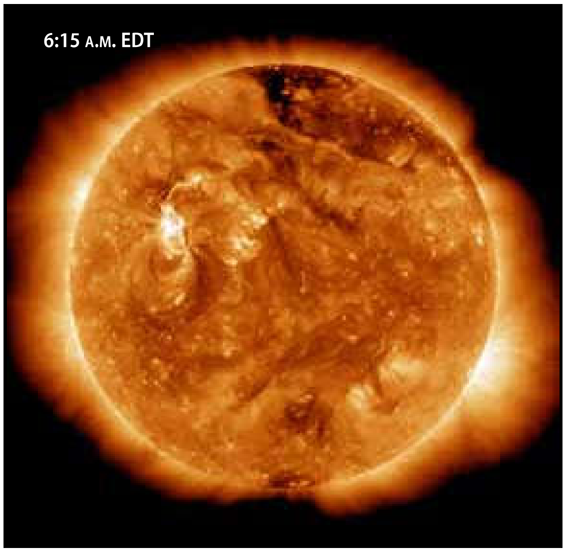
EVE data reveal that most of the energy radiated by a flaring region does not consist of X-rays with wavelengths less than 7nm, but at longer extreme ultraviolet (EUV) wavelengths around 27nm. This has consequences far beyond our understanding of solar flares. Earth's atmosphere absorbs EUV radiation at higher altitudes than it does X-rays, and EUV emissions last longer as well. Both of these observations indicate that scientists need solar spectral measurements in many wavelengths to predict the effects of space weather in our planet's atmosphere.

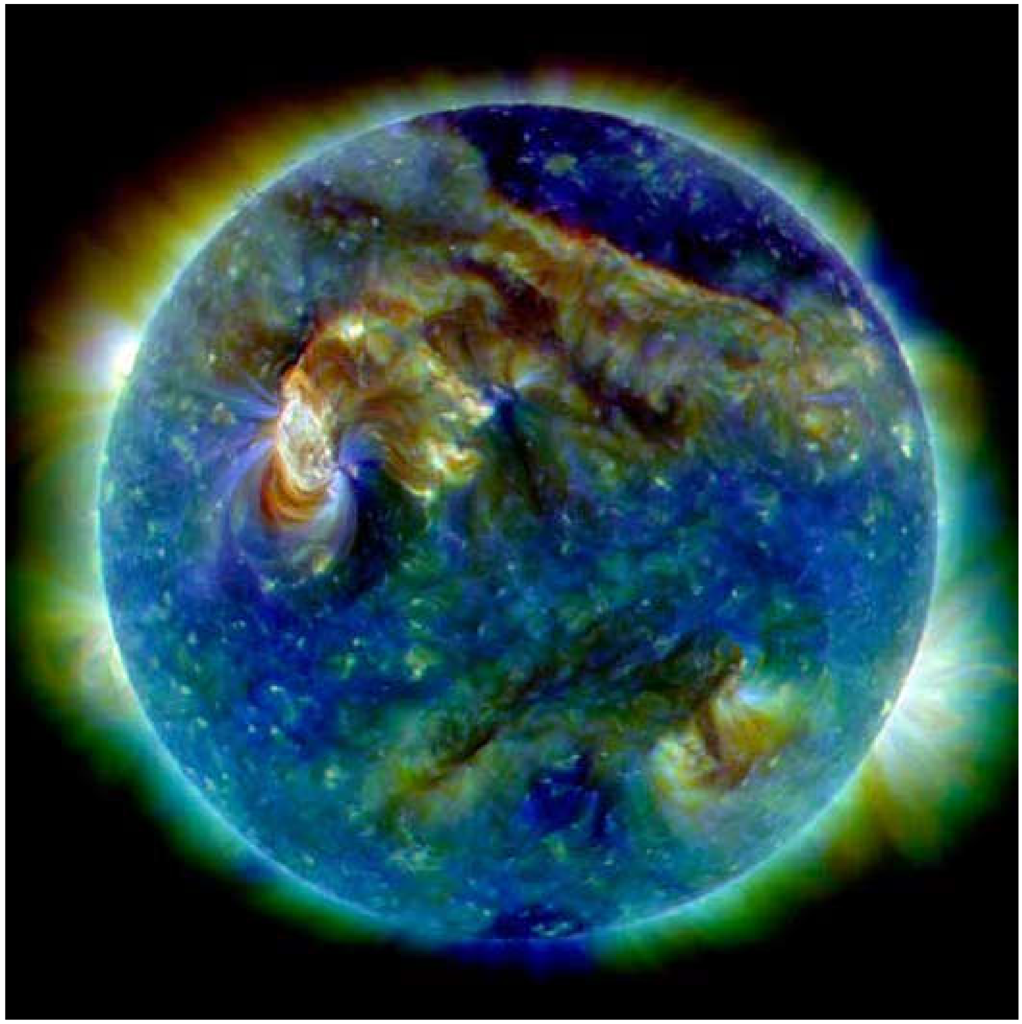
The magnetic field's behavior

Solar physicists have not yet figured out cause and effect of flares, CMEs, and other magnetic phenomena. It's a little like an incident with my young nephew. After dinner one evening, he ran around the family room and hit the wall at full speed just as the furnace coincidentally turned on and warm air rushed into the room. He looked around and said, "It never did that before. I just had to hit the wall harder."

Scientists face a similar situation when they look at the Sun. We already know its magnetic field connects places on the Sun that can be far apart. Flares, prominences, and CMEs happen somewhere on our star almost every day. How can we know whether any two events are related, or whether the "butterfly effect" is at work? If small changes in one place on the Sun can cause large changes in another place, then understanding and predicting its magnetic field becomes far more complicated.

SDO scientists can look at this problem using high-resolution observations across many wavelengths beamed to Earth at a rate of nearly one new image every second. This allows them to see changes propagate across the Sun's disk. They've already seen several examples, but the best



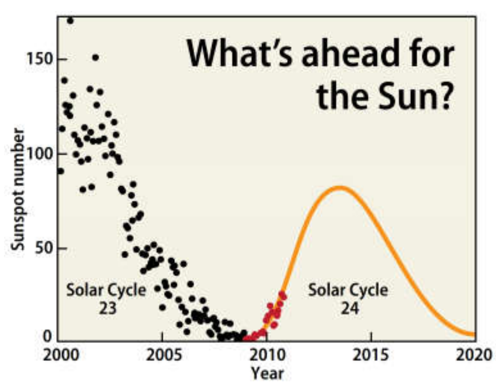


The August 1, 2010, flare (white area at upper left) launched a shock wave whose edge appears at upper right. This view combines data from three extreme ultraviolet wavelengths. NASA/SDO/AIA Science Team

was the August 1, 2010, flare and double CME. (See the images above, which show the Sun in AIA's 19.3nm channel.)

Active region 11092 flared several times early that morning. Although this was only a C-class flare, it affected two filaments whose "foot points" (where the ends enter the Sun's surface) were 185,000 miles (300,000 kilometers) and 280,000 miles (450,000 km) away, respectively.

Soon after the flare, a dimming in the corona spread across the Sun. When this dimming reached the longer filament, it began to lift off the Sun. At about 5:40 A.M. EDT, the filament erupted and launched a CME toward Earth. Afterward, a beautiful arcade of post-eruption loops formed in AIA images and a prairie fire of emission spread out below where the filament had been. Later that day, the second filament also erupted. Although all three events occurred on the same day and in relatively close proximity, SDO scientists still haven't determined cause and effect. Some think the spreading of coronal dimming represents a wave or pulse that links remote areas of the Sun, but others aren't so sure.



No one knows how big Solar Cycle 24 will be. Black dots show cycle 23 observations and red dots cycle 24. The author predicts the current cycle will peak with an average sunspot number of 80. He predicts the peak will occur in late 2013 or early 2014. *Astronomy*: Roen Kelly, after W. Dean Pesnell

Looking in the crystal ball

Given our current knowledge, predicting future solar activity is a huge challenge. Depending on the prediction you read, the current solar cycle (number 24) could be extremely large or nearly absent. (Solar cycles run on a roughly 11-year period from minimum to maximum and back; the current cycle began in 2009 and should end around 2020.)

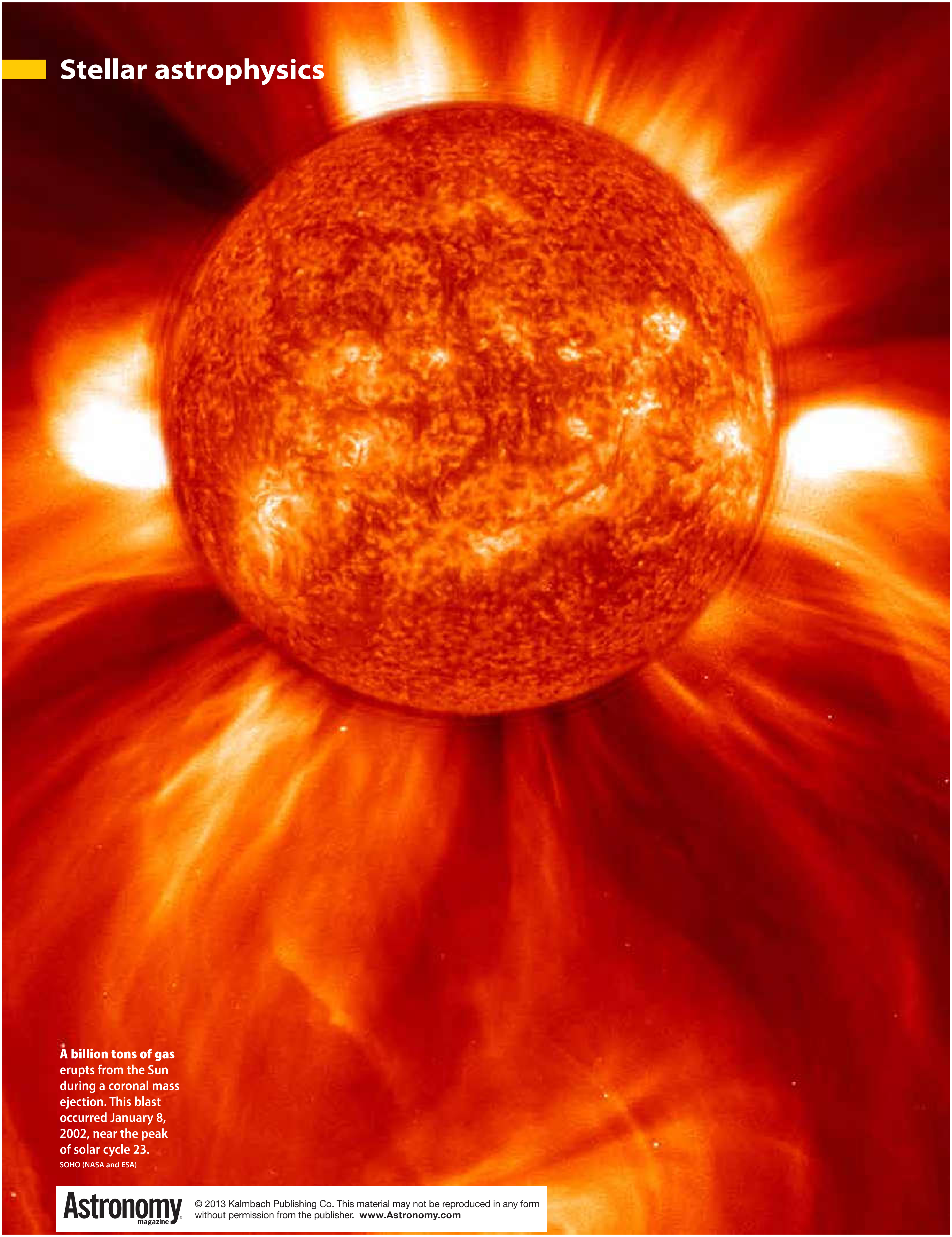
Looking at the Sun's present state, it appears that Solar Cycle 24 will prove below average in terms of the number of sunspots, and also longer than average. This would follow a pattern in sunspot numbers where the Sun's activity level pauses every 100 years or so. But we don't have a clue what Solar Cycle 25 will look like. By combining the rapid increase in data from missions such as SDO with ever-faster computer speeds to run solar models, solar scientists should take big steps forward before Solar Cycle 25 starts around 2020.

The vector magnetograms produced by HMI should help with their predictions. For the first time, solar scientists will have measurements of the strength and direction of the Sun's magnetic field over its visible disk. These data are fast enough for scientists to see changes in the field that coincide with or precede flares and CMEs.

From launch to the present, SDO has yielded information about the Sun and the world around us. Will pulses spreading from central sites serve as the link between the events witnessed at SDO's launch and the solar science it conducts? Time will tell. After all, SDO's 5-year mission to study Solar Cycle 24 has just begun.

Watch SDO videos of the Sun at www.Astronomy.com/toc.

Stellar astrophysics



A billion tons of gas erupts from the Sun during a coronal mass ejection. This blast occurred January 8, 2002, near the peak of solar cycle 23.
SOHO (NASA and ESA)