STEREO as a "Planetary Hazards" Mission

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Abstract

NASA's twin STEREO probes, launched in 2006, have advanced the art and science of space weather forecasting more than any other spacecraft or solar observatory. By surrounding the Sun, they provide previously-impossible early warnings of threats approaching Earth as they develop on the solar far side. They have also revealed the 3D shape and inner structure of CMEs—massive solar storms that can trigger geomagnetic storms when they collide with Earth. This improves the ability of forecasters to anticipate the timing and severity of such events. Moreover, the unique capability of STEREO to track CMEs in three dimensions allows forecasters to make predictions for other planets, giving rise to the possibility of interplanetary space weather forecasting too. STEREO is one of those rare missions for which "planetary hazards" refers to more than one world. The STEREO probes also hold promise for the study of comets and potentially hazardous asteroids.

Keywords
Sun – Heliosphere – CMEs – Space Weather

Introduction

As planetary hazards go, few perils eclipse the Sun. The iconic example is the Carrington event of 1859.

At 11:18 AM on the cloudless morning of Thursday, September 1, 1859, 33-year-old astronomer Richard Carrington was in his well-appointed private observatory. Just as usual on every sunny day, his telescope was projecting an 11-inch-wide image of the Sun on a screen, and Carrington skillfully drew the sunspots he saw.

Suddenly, before his eyes, two brilliant beads of blinding white light appeared over an enormous sunspot group. Realizing that he was witnessing something unprecedented and "being somewhat flurried by the surprise," Carrington later wrote, "I hastily ran to call someone to witness the exhibition with me. On returning within 60 seconds, I was mortified to find that it was already much changed and enfeebled." He and his witness watched the white spots contract to mere pinpoints and disappear.

Thus were solar flares discovered.

Before dawn the next day, skies all over Earth erupted in red, green, and purple auroras so brilliant that newspapers could be read by their light. Stunning auroras pulsated as far south as Cuba, the Bahamas, Jamaica, El Salvador, and Hawaii.

Even more disconcerting, telegraph systems worldwide went haywire. Spark discharges shocked telegraph operators and set telegraph papers on fire. Even when telegraphers disconnected the batteries powering the lines, aurora-induced electric currents in the wires allowed messages to be transmitted. The “Victorian Internet” was simultaneously energized and brought to its knees.

What would happen if such an event occurred today?

The National Academy of Sciences has framed the problem in a landmark report entitled "Severe Space Weather Events—Societal and Economic Impacts" (National Research Council, 2008). It noted how people of the 21st-century rely on high-tech systems for the basics of daily life. Smart power grids, GPS navigation, air travel, financial services and emergency radio communications can all be knocked out by intense solar activity. A century-class solar storm could cause twenty times more economic damage than Hurricane Katrina.

It was once thought that the Carrington event was an extraordinarily rare thing, but that idea is beginning to change. The Carrington event is indeed the undisputed champion of radiation storms: Energetic particles accelerated by the flares of Sept. 1859 enveloped Earth, possibly leaving a record in the nitrates of ice cores. By this measure, the Carrington event may be the biggest in 500 years and nearly twice as big as the runner-up.

However, there is more to space weather than radiation storms. Another measure is geomagnetic activity—the shaking of Earth’s magnetic field due to the impact of a Coronal Mass Ejection/CME (a magnetized cloud of plasma from the Sun). In this respect, the Carrington event has rivals in modern times.

A geomagnetic storm at least half as strong as the Carrington Event erupted in May 1921. John Kappenman of the Metatech Corporation examined geomagnetic records from that storm and modeled its effect on the modern power grid (Kappenman, 2008). In North America alone, he found more than 350 transformers at risk of permanent damage and 130 million people without power. The loss of electricity would ripple across the social infrastructure with water distribution affected within several hours; perishable foods and medications lost in 12-24 hours; and the loss of heating/air conditioning, sewage disposal, phone service, fuel resupply and other services persisting for unknown periods of time.

A more recent example occurred in March 13, 1989, when a strong flare provoked geomagnetic storms that disrupted electric power transmission from the Hydro Québec generating station in Canada. More than 6 million people were plunged into darkness for 9 hours. Aurora-induced power surges melted power transformers as far away as New Jersey.

Much of the damage can be mitigated if managers know a storm is coming. Putting satellites in 'safe mode' and disconnecting transformers can protect these assets from damaging electrical surges. Preventative action, however, requires accurate forecasting—a job that has been assigned to NOAA.

Space weather forecasting is still in its infancy. Many observers liken it to terrestrial weather forecasting—50 years ago. Nevertheless, researchers at NOAA's Space Weather Prediction Center in Boulder, Colorado, are making rapid progress.

Space weather forecasting is actually a collaboration between NASA and NOAA. NASA's fleet of heliophysics research spacecraft provides NOAA with up-to-the-minute information about what is happening on the Sun. The NASA fleet complements NOAA's home-grown GOES and POES satellites, which focus more on the near-Earth environment.

Among many capable solar observatories operated by NASA, one stands out as particularly unique: the twin STEREO probes.

STEREO, short for "Solar TErrestrial RElations Observatory" (Kaiser et al., 2008), is the third mission in NASA's Solar Terrestrial Probes program. It consists of two nearly identical 3-axis-stabilized space-based observatories - one ahead of Earth in its orbit, the other trailing behind – which observe the Sun from multiple (and sometimes stereoscopic) points of view. The two solar-powered probes were launched on October 25, 2006 and they have been beaming back unprecedented data about the Sun ever since.

Mission Overview

The original objective of the STEREO mission was not to provide planetary defense, but rather to conduct fundamental investigations in solar physics. Researchers wanted to investigate the 3D structure and internal magnetohydrodynamic physics of coronal mass ejections (CMEs).

CMEs are key agents of planetary space weather. They are powerful eruptions that can blow up to 10 billion tons of the sun's atmosphere into interplanetary space. A typical CME has a speed of .5-2 million mph (~1-3 million kph), but extremely energetic eruptions have been observed exceeding 5 million mph (8 million kph). When CMEs sweep past Earth, their interaction with our planet's magnetic can spark pronounced geomagnetic activity and storms.

By observing CMEs from multiple points of view, and tracking their progress across the Sun-Earth divide, researchers have been able to make progress on a number of previously-intractable questions. The authors of the mission's 1997 Science Definition Report wanted to know the following:

- Are CMEs driven primarily by magnetic or non-magnetic forces?
- What initiates a CME?
- What is the origin of waves, shocks and particle radiation that often precede a CME's arrival at Earth?

"In order to understand and forecast CMEs," they wrote, "we need 3D images of them and of the ambient solar corona and heliosphere."

It is notable that even in the earliest thought-pieces about the STEREO mission, *forecasting* CMEs appeared alongside *understanding* them. Planetary hazards were on the minds of mission planners from the very beginning.

Figure 1: Diagram of STEREO spacecraft positions from 2007 through 2015. (Courtesy of NASA.)

To accomplish these goals, two spacecraft would be required: one probe orbiting just inside the orbit of Earth and one probe orbiting just outside. STEREO-Ahead (inside) and STEREO-Behind (outside) would drift away from one another, STEREO-A moving ahead of Earth's orbit and STEREO-B behind at a rate of ~22.5 degrees/year, providing the necessary points of view (see Figure 1).

This scheme had another advantage. Within a few years of launch, the separating probes would gain an excellent view of the far side of the Sun. For the first time, NASA could monitor the entire 360-degree circumference of our star. The Sun has a vexing habit of surprising forecasters with sunspots that developed on the far side of the Sun, spitting flares and hurling CMEs when they rotated towards Earth. With STEREO, those days would be a thing of the past.

Mission Characteristics

As with many nascent space missions, one of the first challenges for STEREO was financial. The NASA budget allowed for a single rocket to launch the mission, yet the two probes needed to be placed in significantly different orbits. Mission planners called on the Moon for assistance.

Mission designers realized that they could use the Moon's gravity to redirect the probes to their appropriate orbits - something the launch vehicle alone could not do. For the first three months after launch, the two observatories flew in highly elliptical orbits extending from very close to Earth to just beyond the Moon's orbit. STEREO Mission Operations personnel at the Johns Hopkins University's Applied Physics Laboratory in Laurel, Maryland nudged the spacecraft's orbits closer and closer to the Moon itself. About two months after launch, STEREO-B was close enough to use the Moon's gravity to fling it to a position "behind" Earth. Approximately one month later, STEREO-A encountered the Moon again and was flung to its orbit "ahead" of Earth. This was the first time a “double lunar flyby” had been used to manipulate orbits of multiple spacecraft at the same time.

After their encounters with the Moon, the two STEREO probes were in nearly 1-AU orbits with periods slightly less and slightly more than one year. From the point of view of Earth, STEREO-A would slowly drift ahead of our planet, gaining a view of solar “terrain” previously hidden on one side of the Sun, while STEREO-B would lag behind, providing a view of the other side.

Early in the mission, when the spacecraft separation was small, the viewing angles were ideal for stereoscopic reconstruction of CMEs. *In situ* investigations were able to provide multi-point measurements of the same eruption, providing insight into the structural variation within a particular event.

Later, as the separation increased, STEREO undertook different challenges, such as tracking eruptions all the way from the Sun to Earth. Also, the coronal imagers began to see more and more of the Sun that was hidden from Earth's view, providing the first global observations of the atmosphere of a star.

Figure 2: Left: 3D reprojection of STEREO EUVI and SDO AIA 304 Å images onto a solar sphere. Right: 360° maps of the full solar corona in September 2012, when the STEREO and SDO spacecraft achieved maximum average separation (120°). From top to bottom, the EUVI/AIA wavelengths represented are 304Å, 171Å, and 193/195Å. (Courtesy of the STEREO/SECCHI consortium.)

At first, the twin spacecraft saw only a fraction of the Sun’s far side, but as they continued to drift apart the view improved. On February 6, 2011, STEREO reached "opposition.” The two probes were 180 degrees apart, each looking down on a different hemisphere. Coincidentally, this occurred on Super Bowl Sunday in the USA, and NASA Public Affairs took advantage of the occasion to release a “first light” 3D movie of the Sun. For the first time in the history of astrophysics, researchers could see and study a star as a fully-realized sphere as we regularly do with Earth (see Figure 2).

NASA's Earth-orbiting Solar Dynamics Observatory is also monitoring the Sun from its location in Earth orbit. Working together, the STEREO-SDO fleet will be able to image the entire 3D Sun until May/June 2019 (apart from periods when the STEREO spacecraft are too close to the Sun-Earth line to allow communication).

Can STEREO last that long? Originally, STEREO was conceived as a 2 ½ year mission, but that idea was quickly scrapped. Such a short mission would never reveal the full expanse of the far side of the Sun. Also, in early designs, there had been a limit on the movement of the high-gain antenna which would have curtailed operations to approximately 2013. The Applied Physics Lab removed that limit at the request of the NASA project office, and now there is no impediment (other than funding) to continuing on for many more years. The spacecraft's solar arrays can provide power for any reasonable extension of the program. Both spacecraft have passed the point of "infant mortality" – that is, systems failing early -- but of course electronics can fail at any time in response to cosmic rays and, ironically, solar storms.

Scientific Investigations

Getting the probes into their correct orbits, and engineering them to last more than a decade were significant technical challenges. Even more challenging, however, are the mission's scientific requirements.

To fully understand the genesis, evolution, and planetary impacts of CMEs, the STEREO probes would have to have a dynamic range of sensitivity unlike any other observatory in NASA's history. Researchers needed to see (1) intensely-bright explosions near the Sun's surface, (2) moderately-bright CMEs ram-rodding out of the Sun's atmosphere, and (3) the vanishingly-faint remains of CMEs expanding into the near-vacuum of interplanetary space. Moreover, to understand the environment of CMEs, STEREO would also need to image the solar wind itself, flowing almost transparently in and around the storm cloud.

No single telescope could do the job alone. Designers therefore equipped STEREO with a package of five telescopes in the SECCHI investigation (Howard et al., 2008), each operating in a different range of brightness and observing events at different distances from the Sun.

The first SECCHI telescope is the Extreme Ultraviolet Imager (EUVI) built at the Lockheed Solar and Astrophysics Laboratory in Palo Alto, California. EUVI is able to make high-resolution (2k x 2k) images of the Sun and its lower atmosphere in four different extreme ultraviolet emission lines: 171, 193, 284 and 304 Angstroms. The four wavelengths were selected to trace plasma temperatures and magnetic conditions of special interest to solar physicists who wish to study the onset of explosions such as flares and CMEs. The Extreme Ultraviolet Imager observes the Sun between 1 and 1.7 radii from disk center—in other words, it monitors the bright solar surface, the chromosphere, and the inner corona.

Figure 3: Four of the SECCHI telescopes from both STEREO-A and STEREO-B were used to reconstruct the 3D propagation toward Earth. Not shown is the HI2 outer heliospheric imager. (Figure reproduced from Byrne et al., 2010.)

Next is the inner coronagraph, known as COR1. Coronagraphs are devices that create an artificial eclipse using an opaque disk to block the glare of the Sun. Built at Goddard Space Flight Center, COR1 is a classic "Lyot internally occulting refractive coronagraph" adapted for the first time to be used in space. COR1's field of view ranges from 1.4 to 4 solar radii, so there is some overlap with the Extreme Ultraviolet Imager. Unlike EUVI, however, COR1 is designed to observe fainter things—primarily the gossamer solar corona and CMEs which plow through it en route to Earth. Although the Sun is blocked by an occulting disk, scattered light in the optical path of COR1 can still be a problem. To mitigate this, COR1 is equipped with a linear polarizer to suppress scattered light, and to extract the polarized brightness signal from the solar corona.

When engineers have to build a telescope that spends all of its time staring into the Sun, special measures must be taken to handle thermal loads and protect sensitive components. COR1 is a good example of how STEREO engineers dealt with these problems.

Because the two STEREO spacecraft are in elliptical orbits about the Sun, the COR1 instruments experience considerable variation in solar irradiance, from 1264 to 1769 W/m^2 for STEREO-A and from 1068 to 1482 W/m^2 for STEREO-B. When these loads are combined with expected changes in the telescope's material thermal properties from beginning to end of life, the worst-case temperature variation in the COR1 instrument is from 2.5 to 30° C. There's also an axial gradient in temperature from the front to the back of the telescope, ranging from 3° C to 7° C.

To deal with such gradients, designers placed software-controlled heaters with programmable set points at strategic locations throughout the instrument. They keep the instrument within the 0-40° C operational temperature range. There are also survival heaters controlled by mechanical thermostats to keep the instrument within the -20 to +55° C non-operational range.

Other measures also help the instrument deal with intense solar heat. For instance, specialized composite coatings of oxides over silver are deposited onto many exposed surfaces around the telescope's aperture, such as the objective lens holder and door assemblies. These stable coatings absorb little sunlight and do a good job re-radiating what they do absorb as infrared radiation.

Another "hot spot" is the tip of the coronagraph's occulting device. A majority of the solar load collected by the telescope's main lens is concentrated there, raising its temperature as high as 125° C. This tip is made of titanium, and is diamond-turned to direct the sunlight into a light trap. The tip is also coated with a composite silver coating for high reflectivity. To further cool things down, the shaft of the occulting device is coated with black nickel to radiate away even more heat.

"Managing heat is a challenge for any solar observatory. A detailed discussion of heat management techniques and the extensive thermal engineering required for all of STEREO's telescopes is beyond the scope of this chapter. Suffice it to say that all five telescopes have employed an innovative array of tricks to keep things cool."

The third SECCHI telescope is the outer coronagraph, known as COR2. Unlike COR1, which blocks the Sun inside the telescope assembly, COR2 is an externally-occulted Lyot coronagraph. Designed and built at the Naval Research Laboratory in Washington DC, COR2 is a descendant of the highly successful LASCO C2 and C3 coronagraphs onboard the Solar and Heliospheric Observatory (SOHO). COR2 has approximately the same field of view as the two SOHO coronagraphs combined, and is able to take pictures with a much shorter exposure time to reveal faster dynamics of CMEs, all while fitting into a smaller space inside its spacecraft. COR2 can track CMEs out to 15 solar radii when they are exiting the Sun's atmosphere and entering interplanetary space.

SECCHI's COR1 and COR2 observations are complementary to SOHO's C2 and C3 coronagraphs, which provide observations from Earth's point of view. With SOHO's view from Earth and SECCHI's additional views, the three comprise a powerful 3D viewing assembly for CMEs.

Fourth and fifth are, arguably, the most amazing telescopes of all—STEREO's Heliospheric Imagers. The Heliospheric Imagers monitor a vast realm of space extending from the Sun's upper atmosphere all the way to the orbit of Earth. They can track CMEs uninterrupted over a gulf of more than 93 million miles. By the time these storm clouds travel so far from the Sun, they are very faint, 13-15 orders of magnitude fainter than the solar disk. The HI instruments must be able to see them against a busy background of stars, planets, and even comets that sometimes get in the way.

The Heliospheric Imagers consist of two small wide-angle telescopes mounted on the side of the STEREO spacecraft. They are sheltered from the glare of the Sun by a series of linear occulters. Unlike the coronagraphs, which put an occulter directly in front of the Sun to reduce glare, HI operates in the shade of a more conventional baffle. The concept is not unlike observing the night sky after the Sun has gone below the horizon. One telescope (HI-1) sees a patch of sky about 20 degrees wide, the other (HI-2) sees 70 degrees, extending beyond the orbit of Earth. The fields of view overlap by about 5 degrees, to allow continuous tracking from the inner heliosphere to beyond 1AU.

The greatest challenge for HI is the extreme faintness of CMEs. Background starlight from the Milky Way and the glow of sunlight scattered by interplanetary dust (zodiacal light) tend to overwhelm the gossamer clouds. In order to extract the CME signal, the signal-to-noise ratio must be increased over what is possible with a single exposure. Exposures are therefore summed on-board. This requires that the images be scrubbed for cosmic rays, which can make bright streaks and flashes in individual exposures, prior to summing. A 2x2 binning results in angular sizes of 70 arcsec per pixel for HI-1 and 4 arcmin per pixel for HI-2. . The combination of summing 50 images and 2x2 binning results in an increase in signal to noise ratio of about 14 times for HI-1. The effective exposures are 20 and 60 arc minutes for HI-1 & HI-2 respectively.

Powerful image processing techniques, specifically developed for STEREO's HI imagers, have further enabled the ability to view event faint eruptions. Figure 4 shows three different CMEs in the STEREO-A SECCHI combined field of view, tracking their transit over the course of several days.

Figure 4: Composite imagery from the five SECCHI telescopes showing three CMEs on January 9, 2009: one in the COR2 field of view, one in HI-1, and one reaching 1 AU in HI-2. Three planets are also shown: the blue dot represents Earth, pink indicates Venus, and yellow indicates Mercury. (Courtesy of C. E. DeForest, see DeForest et al. 2011, 2013)

The result of this processing is a high dynamic range, wide-field image capable of recording stars as faint as 12th magnitude alongside planets orders of magnitude brighter. Indeed, Earth itself often appears in HI images. From their locations over the far side of the Sun, the STEREO probes can look back and see our home planet—a key requirement in tracking CMEs across the Sun-Earth divide.

When all of its telescopes are operating nominally, STEREO can simultaneously observe objects as bright as the Sun (astronomical magnitude -27) and as dim as a 12th magnitude star. That gives the probes a dynamic range approximately 10 billion times greater than the human eye. STEREO can detect flashes as intense as a solar flare and as faint as a charcoal-black asteroid approaching Earth from the direction of the Sun--and everything in between. No other astrophysics observatory has this kind of Olympic range.

STEREO is also able to detect radio emissions from a variety of shock waves and plasma oscillations excited by flares and CME. It does this using the SWAVES instrument package: Three mutually orthogonal monopole antenna elements, each 6 meters in length, jut out of the spacecraft to sample electrostatic and electromagnetic waves. The antennas are connected to five radio receivers variously sensitive to frequencies between 10 kHz and 50 MHz. Working together, these receivers can pick up Type II, III, and IV "solar radio bursts" indicative of shocks and energetic particle interactions (see Figure 5) as well as a variety of *in situ* plasma modes such as Langmuir, whistler, Z-mode and electrostatic solitary waves (Bougeret et al., 2008).

Figure 5: Detection of radio bursts associated with a flare, CME, and post-eruptive loops on the Sun (shown in the upper left corner). CMEs do not propagate through a vacuum. On their way to Earth, they interact with shock waves, solar wind streams and other gaseous “obstacles.” Indeed, the interaction of CMEs with the interplanetary medium can be a source of hazards to Earth and astronauts: Shock waves at the leading edge of CMEs can accelerate particles in the interplanetary medium to dangerous velocity. Studying the CME by itself is not enough. The

structure of the medium it propagates through is equally important. (Courtesy of N. Gopalswamy)

In situ measurements of particles and fields are provided by two STEREO investigations: IMPACT and PLASTIC. The IMPACT (In-Situ Measurements of Particles and CME Transients; Luhmann et al., 2008) investigation is comprised of 7 instruments: SWEA (Solar Wind Electron Analyzer), STE (Suprathermal Electron Telescope), MAG (Magnetometer), SEPT (Solar Electron Proton Telescope), SIT (Suprathermal Ion Telescope), LET (Low Energy Telescope) and HET (High Energy Telescope). SWEA measures solar wind electrons from below an eV to several keV, while STE covers 2-20 keV electrons, SEPT covers 20-400 keV, and HET covers .7-6 MeV. Protons are measured by SIT, SEPT (20-7000 keV), LET (2-30 MeV), and HET (13-100 MeV), while measurements of helium and heavier elements are provided by SIT, LET and HET. The MAG system provides magnetic field measurements in three dimensions, and is divided into eight ranges to allow the capability of measuring a wide variety of magnetic field strengths.

The PLASTIC (Plasma and Suprathermal Ion Composition; Galvin et al., 2008) investigation consists of three main components. The Solar Wind Sector (SWS) Small Channel provides a 45° field of view of solar wind protons and alpha particles, while the SWS Main Channel measures elemental composition and charge state properties and velocities for heavier ions. The Wide-Angle Partition (WAP) Sector has a 225° field of view on STEREO-A (210° on STEREO-B), representing the remaining unobstructed directions not covered by the SWS components. All three components deliver measurements at a time resolution of 1 minute. The PLASTIC entrance system is an energy-per-charge analyzer, and the resulting energy ranges are .3-10.6 keV/e for SWS Small Channel, .3-80 keV/e for SWS Main Channel, and .3-80 keV/e for WAP.

The IMPACT/PLASTIC *in situ* suite on STEREO has advanced our understanding of interplanetary hazards for several major reasons. Multi-point *in situ* measurements of major events have provided a dramatic improvement in our understanding of the 3D structure of space weather phenomena. The manifestations of hazard-causing phenomena are far from homogeneous in structure. When two spacecraft are able to sample the same event, the data frequently reveal great variations. Multi-point measurements have improved our ability to complete a 3D picture of these complex phenomena. Notably, both STEREO probes detected the historic radiation storm of July 2012, when a sunspot erupted and produced one of the most prolific streams of energetic protons in the history of the Space Age. Earth was not in the line of fire and, without STEREO, researchers might not have known the event occurred at all. By sampling the storm from points far from Earth, the STEREO probes replaced that cloud of ignorance with a wealth of IMPACT/PLASTIC data that researchers are still studying years later.

The IMPACT/PLASTIC combination has also drastically improved our ability to understand the 3D structure of the heliosphere. It has long been known that the Sun is only the beginning of the story. CMEs, energetic particles and shocks are strongly modulated by the solar wind through which they propagate. Heliospheric structure is capable of speeding up, slowing down, or even deflecting CMEs. It can also enhance or decrease the magnitude of the hazard; for example, extremely high-energy proton events, which pose the greatest risk to assets in space, are produced by the interaction of a CME and shocked solar wind. These protons then travel along the solar wind magnetic field; without knowledge of the magnetic structure of the heliosphere, it is impossible to determine where or how strongly an energetic particle event will manifest itself.

STEREO Space Weather Beacon Data

In support of space weather forecasting capabilities, each of the investigations on the two STEREO spacecraft also generate a special low-rate telemetry stream known as the Space Weather Beacon. Outside of the regular Deep Space Network contacts, which deliver the full science data, this Space Weather Beacon stream consists of a low-rate subset of the data specifically designed to allow rapid assessment of the space environment. Various antenna partners around the world collect this telemetry and pass it on to the Stereo Science Center (SSC) in near-real-time via a socket connection over the open internet. The Space Weather Beacon allows forecasters and other users to access critical data days before the high-rate science data becomes available.

Key Findings and Results

CME Topology

The STEREO mission has achieved its major goal--the three-dimensional modeling of CMEs. From our single vantage point on Earth, CMEs flying in all directions away from the Sun appear to have a confusing variety of forms. Indeed, researchers had spent years examining thousands of CMEs recorded by Earth-orbiting cameras without finding the answer. As soon as STEREO was added to the mix, however, a common form emerged: CMEs resemble croissants (Figure 6).

Actually, theoretical models had predicted this for some time. A croissant shape naturally results from coiled magnetic fields called “flux ropes” widely believed to thread through the hearts of CMEs. Three-dimensional STEREO observations removed any doubt that this was the case (Vourlidas et al., 2013). Follow-up observations by NASA’s Solar Dynamics Observatory have revealed flux ropes near the solar surface that twist and break away to form CMEs (Patsourakos et al., 2012). Although the structure of CMEs can evolve significantly as they propagate, the croissant/flux rope model is now on a very firm footing.

Figure 6: 3D flux rope reconstruction of a CME on March 7, 2011 using the Thernisien, Howard & Vourlidas (2006) "croissant" model. The model allows an accurate determination of the spatial extent of a CME, and can track the temporal evolution as the CME propagates in the inner corona. (Courtesy of the STEREO/SECCHI consortium and A. Thernisien.)

This is crucial for two reasons. First, even with STEREO on duty, CMEs leaving the Sun are not always observed from multiple points of view. Knowing the common shape of a CME allows forecasters to model its speed and trajectory using less-than-complete data. This improves the precision of forecast CME impact times. Second, the ability of a CME to foment a magnetic storm on Earth depends critically on its inner magnetic structure. Knowing the form of the magnetic structure—it's a *flux rope*—helpfully narrows the options for modelers who try to anticipate what a CME will do when it arrives. In 2014, forecasters are still struggling to weave this information into their forecasts. It is just a matter of time, however, before flux rope models improve the fidelity of geomagnetic storm warnings.

The Drivers of Solar Eruptions

The full-sun view afforded by STEREO and supporting observatories does more than improve space weather forecasts. It has led to a whole new understanding of solar activity.

For decades, astronomers have understood solar activity in terms of localized regions on the Sun. When the magnetic fields of individual sunspots criss-cross and reconnect, powerful explosions ensue. This is how flares and CMEs happen.

On August 1, 2010, this simple idea was upset. On that date the STEREO-SDO fleet observed a massive global series of explosions engulfing more than two-thirds of the Sun. Researchers catalogued more than a dozen significant shock waves, flares, filament eruptions, and CMEs spanning 180 degrees of solar longitude and 28 hours of time (Schrijver & Title, 2011). At first it seemed to be a cacophony of disorder until they plotted the events on a map of the Sun's magnetic field. The events were connected by magnetism, one explosion triggering another like a series of falling dominoes.

Solar physicists had long suspected this kind of magnetic connection was possible. The notion of "sympathetic flares" goes back at least three quarters of a century. 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 often full of doubt.

For this kind of work, STEREO and SDO are game-changers. Together, the three spacecraft allow researchers to see connections that they could only guess at in the past. To wit, only a fraction of the August events were visible from Earth, yet all of them could be seen by the SDO-STEREO fleet. Moreover, SDO's measurements of the Sun's magnetic field revealed direct connections between the various components of the "Great Eruption"—no statistics required.

Much remains to be done. Researchers are still unsure about the timing: 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? The next global eruption observed by STEREO --and, yes, there will be a next one--could answer these questions.

Sun-to-Earth Observations

For many years, a “holy grail” of space weather forecasting has been to track a CME all the way from the Sun to Earth. STEREO has accomplished this, too.

In December 2008, STEREO-A was 65 million km from Earth when a CME sped away from the Sun. The cloud remained in STEREO-A’s field of view as it propagated all the way across the Sun-Earth divide.

When CMEs first leave the Sun, they are bright and easy to see. Visibility is quickly reduced, however, as the clouds expand into the void. By the time a typical CME crosses the orbit of Venus, it is a billion times fainter than the surface of the full Moon, and more than a thousand times fainter than the Milky Way. CMEs that reach Earth are almost as gossamer as vacuum itself and correspondingly transparent.

Even with STEREO’s onboard image enhancements described earlier in this chapter, it was an enormous challenge to pull such a faint cloud out of the confusion of starlight and interplanetary dust. Indeed, it took almost three years for the researchers to learn how to do it. Footage of the 2008 storm wasn’t released until 2011! Now that the technique has been perfected, it can be applied on a regular basis without such a long delay (DeForest, 2011).

If Sun-to-Earth CME tracking can be sped up and perfected, it would lead to a revolution in space weather forecasting. For one thing, forecasters would know exactly when and where a CME is going to strike. Uncertainties could be narrowed to the point that forecasts of space weather effects on Earth could become regional, rather than merely global as they are now. Tracking a CME continuously from Sun to Earth also means that forecasters could watch the cloud’s magnetic evolution and accurately anticipate its degree of “coupling” with Earth’s own magnetic field. They would know exactly what kind of geomagnetic storm is in the offing.

These dramatic improvements, however, are still in the future. They require processing times to be reduced from years to hours, so there are huge practical challenges yet to overcome. Nevertheless, STEREO has shown us the possibilities.

Interplanetary Space Weather

While one revolution waits, another is already underway—the revolution of Interplanetary Space Weather Forecasting (Guhathakurta, 2013).

Figure 7: Sunspot AR1429 unleashed a powerful X5-class solar flare on March 7, 2012, commencing the "St. Patrick Day storms" of 2012. The blast also propelled a massive coronal mass ejection (CME) toward Earth. Left: NASA's Solar Dynamics Observatory recorded the flare at multiple extreme ultraviolet wavelengths. (Courtesy of the SDO/AIA consortium.) Right: A 3D CME model run from CCMC/iSWA shows how the CME would propagate through the inner solar system. (Courtesy of the Community Coordinated Modeling Center.)

Researchers working with STEREO's 3D CME models quickly realized that they could make predictions not only for Earth, but also for any other target in the solar system. The "planet" in "planetary hazards" could be any world from Mercury to Neptune.

Tracking CMEs through the plasma-filled interplanetary medium takes more than a quick glance at data streaming in from the fleet. High-power computing is required. Around the time STEREO was launched, international researchers began to install their best physics-based models of the heliosphere on a bank of high-speed supercomputers at the Community Coordinated Modeling Center (CCMC), an interagency facility located at Goddard. NASA also established the Integrated Space Weather Analysis System (iSWA) to fetch space weather information from a wide array of spacecraft and sensors. Together, these programs can take raw data from the STEREO-SDO-SOHO fleet and turn them into meaningful space weather forecasts for any point in the solar system.

Interplanetary space weather forecasting is important to NASA and other space agencies as probes are now orbiting or en route to Mercury, Venus, the Moon, Mars, Ceres, Saturn, Jupiter and Pluto. Each mission has a unique need to know when a solar storm will pass through its corner of space.

This is illustrated by the ironic example of MARIE on Mars Odyssey. The sensor, designed to measure space radiation in the vicinity of the Red Planet, was disabled by a fusillade of solar protons during the Halloween storms of 2003. Turning MARIE off during the storm might have saved it, but no one knew the protons were coming. Controllers of ongoing missions such as MAVEN and Curiosity would like Mars-specific warnings to help them safeguard their hardware.

Earth's satellite fleet is similarly exposed. A widely-reported example is Galaxy 15: In April of 2010, a minor CME swept past Earth just as the massive telecommunications satellite was coming out of Earth's shadow. What happened next is still controversial, but many researchers believe events unfolded as follows: Suddenly exposed to hot, energetic electrons stirred up by the CME, the satellite began to bristle with electricity. Electrons accumulated on the surface of Galaxy 15 until a sudden discharge turned the comsat into a "zombiesat." It stopped accepting commands from Earth and spent the next 8 months drifting through the Clarke Belt broadcasting its own signals atop those of other satellites until it was recovered. Future episodes like this may be prevented if NOAA forecasters can pinpoint when CMEs will arrive and warn satellite operators to put their assets in safe mode at crucial moments. It might seem that Galaxy 15 hardly calls for an interplanetary forecast. However, the same 3D CME modeling that permits forecasts for Mercury, Venus and Mars also offers substantially improved forecasts for our own planet.

Modern Superstorms

As mentioned previously, the iconic example of space weather hazards is the Carrington event of 1859. Because of STEREO, researchers were able to study a recent eruption that has been compared to the Carrington event in terms of geoeffectiveness, and few events exemplify STEREO's full capability better than the July 23, 2012 CME. The eruption was, for the most part, directed away from geospace; however, the STEREO spacecraft were able to record one of the fastest CMEs ever observed (Russell et al., 2013) and the most intense solar energetic particle event in decades (Mewaldt et al., 2014). Baker et al. (2013) demonstrated, by combining observations and state-of-the art models, that if the CME had been directed towards Earth *it likely would have had a much larger impact than the Carrington storm.* Despite being launched into the weakest solar cycle of the space age, STEREO was able to capture what could have been the storm of the century, had it impacted Earth.

Figure 8: Three views of the July 23, 2012 CME: STEREO-B COR2, SOHO LASCO C3, and STEREO-A COR2. (Courtesy of the STEREO/SECCHI consortium).

Figure 8 shows three views of the coronal mass ejection on 23 July 2012 as observed by the SOHO C3 and STEREO C2 coronagraphs. The multiple viewpoints allowed for a clear determination of the speed and direction of the eruption, and detection in the STEREO heliospheric imagers and *in situ* extended the speed measurements to 1AU. The CME's initial speed was determined to be 2500±500 km/sec, with a width of 140±30 degrees. These parameters were used to drive simulations to determine the CME's propagation through the heliospheric medium. Figure 9 shows the density impact of the CME as determined by the Wang-Sheeley-Arge (WSA)-ENLIL (Arge and Pizzo, 2000; Odstrcil et al., 2004) simulation.

SWAVES added valuable information about the leading edge of the shock of the CME, determining from Type II drift frequencies that the leading edge of the shock was traveling at ~3000 km/sec (Figure 9). The shock extended over 240 degrees in longitude, as most of the inner heliosphere felt the impact of the eruption.

Figure 9: Left: The measurements derived from the multiple viewing angles of the July 2012 CME were then used as input to simulations. 3D models forecast the propagation and evolution of the CME in the inner heliosphere. Although the CME had a dramatic impact on much of the inner heliosphere, fortunately the majority of inner heliospheric space assets were clustered in less impacted longitudes. (Courtesy of the Community Coordinated Modeling Center.) Right: Radio bursts from the CME shock front as measured by STEREO-A SWAVES. (Courtesy of N. Gopalswamy.)

The increased energetic particle fluxes were detected almost immediately, and the shock and CME were detected *in situ* later in the day (around 21:00 UT), when solar wind speeds spiked to over 2000 km/sec and the magnetic field strength increased to over 100 nT (see Figure 10). The 19-hour CME transit time from the Sun to 1 AU is the fastest ever measured directly, as the 17-hour transit time of the Carrington event was inferred from the flare and the geospace impacts.

Although the transit time was slightly longer than the Carrington event, the estimated geomagnetic impact based on models described in Baker et al. (2013) indicates that if the CME had impacted Earth, the storm would have been even greater than the famous 1859 Carrington storm. Without STEREO, little information would have been available on this "modern" Carrington event, and we would have missed the opportunity to study what could have been the storm of the century. In addition, thanks to STEREO, we now know that huge potentially damaging events can occur at any phase of the solar cycle irrespective of the degree of sunspot activity.

Figure 10: The July 23, 2012 CME was detected at STEREO-A only 19 hours after the eruption, the fastest transit ever measured. The bottom panel shows the local solar wind speed detected by STEREO-A PLASTIC, the middle panel shows the magnetic field measurements from STEREO-A IMPACT, and the upper panel shows the IMPACT SEPT, LET and HET energetic proton measurements. (Figure adapted from Russell et. al, 2013)

Interplanetary "Nanodust"

Another discovery by STEREO is not a hazard to planets, but it could be a hazard to spacecraft moving rapidly through interplanetary space. The discovery is “nanodust.”

The solar system is choked full with dust. We see these particles disintegrating in the night sky as meteors, and we see them in even greater numbers scattering sunlight from the plane of the solar system. Observers call it the “Zodiacal Light.”

Figure 11: Dust trails as detected by the STEREO-A HI1 imager on May 1, 2007. The image at right shows the HI-1 image in the left image with a prior image subtracted from it, thereby enhancing the dust trails. (Courtesy of the STEREO/SECCHI consortium. See St. Cyr et al., 2009)

Nanodust is much smaller than these ordinary forms of space dust. Nanodust particles lie at the frontier between macroscopic objects and atomic structures. Unlike regular dust, which is mainly controlled by the gravitational field of the Sun, nanodust grains have a high electric charge relative to their mass, and therefore strongly interact with the solar wind's magnetic field. The solar wind sweeps up grains of nanodust and accelerates them to velocities of hundreds of kilometers per second (a million mph) near Earth’s orbit. These microscopic bullets can create surface charges on the hulls of interplanetary spacecraft.

Indeed, this is how STEREO found them, using SWAVES. Each of the twin probes has a long antenna for sensing radio waves generated by CMEs plowing through the Sun’s atmosphere and, later, through the interplanetary medium. When a grain of nanodust hits STEREO at high velocity, it “craters out” and ionizes some of the spacecraft’s surface material. Impacts close enough to an SWAVES antenna produce a voltage pulse. Researchers counted these pulses to determine the flux of grains in the 5 to 20 nanometer size range. They found, surprisingly, that the population of nanodust makes up a significant fraction of the total mass of dust in interplanetary space (Le Chat et al., 2013).

Comets

Finally, the STEREO probes have made exciting new observations of comets. It started with Comet Encke in 2007.

Amateur astronomers know Comet Encke it is the source of the Taurid meteor shower, a slow display of midnight fireballs that occurs every year in early- to mid-November. Every 3.3 years, the comet dips inside the orbit of Mercury where it is exposed to solar activity at point blank range.

In April 2007, only six months after the mission launched, STEREO-Ahead watched a CME strike the comet and rip off its tail. CMEs have surely collided with comets before, but this was the first time a spacecraft had witnessed the process.

At first glance, it might seem surprising that a CME could rip off Encke’s tail. For all their mass and power, CMEs are spread over a large volume of space. The impact of a gossamer CME exerts little more than a few nanopascals of mechanical pressure—softer than a baby's breath. Therefore, the ripping action must be due to something else. Researchers now believe the explanation is “magnetic reconnection.” Magnetic fields around the comet bumped into oppositely directed magnetic fields in the CME. Suddenly, these fields linked together--they "reconnected"--releasing a burst of energy that tore off the comet's tail. A similar process takes place in Earth's magnetosphere during geomagnetic storms powering, among other things, the aurora borealis.

In a sense, the comet experienced a geomagnetic storm. It is the first time astronomers witnessed such an event on another cosmic body.

Four years later, in December 2011, STEREO was joined by an armada of solar observatories in watching Comet Lovejoy plunge through the Sun's atmosphere. In this case, it was the Solar Dynamics Observatory, not STEREO, which had the best view. Dramatic SDO movies showed the Sungrazing comet's tail veering back and forth as it was buffeted by magnetic structures in the solar corona. Movies of these interactions have sparked a number of studies on how comets can be used as "solar probes." Just as you can learn about the hydrodynamics of a pond by tossing a stone into it and watching the ripples, you can learn about the *magneto*hydrodynamics of the solar corona by watching comets fly through.

Figure 12: This series of three still images were taken from a visualization of Comet Encke flying through the solar storm as witnessed by the STEREO satellite. Note Encke's tail being torn off by the coronal mass ejection, highlighted by the red line, in the second and third frames. (Courtesy of A. Vourlidas and R. A. Howard, see Vourlidas et al., 2007)

STEREO took center stage again when Comet ISON approached the Sun in 2013. The Heliospheric Imagers on STEREO-A tracked the comet from the orbit of Earth all the way to the doorstep of the Sun's atmosphere. No other observatory in space or on Earth could match the quality of the movies STEREO obtained. Footage showed gusts of solar wind buffeting the comet, whirls and eddies of plasma propagating down the comet's tail, and even a remarkable conjunction between Comet ISON and Comet Encke. When ISON entered the Sun's atmosphere, STEREO's coronagraphs followed the action as the comet, lamentably, broke apart. It turns out that Comet ISON was not as tough as its predecessor Comet Lovejoy, so it did not survive its brush with solar fire. STEREO's coronagraphs and Heliospheric Imagers watched as a cloud of dust emerged where Comet ISON was supposed to be—and quickly faded into the black void of space. On the bright side, STEREO and other observatories such as SOHO had a ringside seat for the disruption of a comet, an event which researchers are enthusiastically studying even now.

"Sun as a Star" Studies

Although STEREO is primarily a solar mission, the team realized that the stability of the Heliospheric Imagers (HI) aboard the twin spacecraft could be used to monitor variations in the brightness of stars (Wraight et al., 2012). Researchers have discovered 122 new eclipsing binary stars and observed hundreds more variable stars in an innovative survey using STEREO. STEREO's ability to sample continuously for up to 20 days, coupled with repeat viewings from the spacecraft during the year, makes it an invaluable resource for researching variable stars. Observations from the HI cameras are enabling scientists to pin down the periods of known variables with much greater accuracy. In addition, HI measurements may be useful for exoplanet and astroseismology research (Wraight et al., 2011). Very small changes to the brightness of stars can be detected, which could reveal the presence of transiting exoplanets, or trace a star's internal structure by measuring their seismic activity. One such case has been already identified using HI data.

Figure 13. NASA's STEREO Spacecraft Discovers New Eclipsing Binary Stars: A STEREO Heliospheric Imager (HI-1A) image taken on March 7, 2010 (left) with two variable stars highlighted in the image. The varying brightness of the two stars, V837 Tau and V1129 Tau are shown (right top and bottom, respectively). (Courtesy of D. Bewsher and the STEREO/SECCHI consortium.)

The twin STEREO probes have proven to be among the most versatile spacecraft ever launched. Nevertheless, there is still one area where they have not yet "spread their wings"--the search for potentially hazardous asteroids. Asteroids approaching Earth from the direction of the Sun are among the most difficult to detect by ground-based observatories. Detecting faint objects in the vicinity of the Sun, however, is STEREO's specialty. The Heliospheric Imagers could prove to be useful tools for asteroid hunters, but this is not a capability that researchers are exploiting. This should be considered a small omission, though, given the scope of STEREO's accomplishments so far.

Conclusions

When the words "planetary hazards" are spoken, most people (lay and scientist alike) probably think of asteroids. Yet when was the last time an asteroid did serious damage to human civilization? The Tunguska Event of 1918 leveled a forest, not a city, and the Chelyabinsk Meteor of 2013, which exploded over a populated area in the Urals of Russia did little more than break some windows. This is not to say that asteroids are safe; they most certainly are not. However, to find a recent example of substantial damage to human interests caused by a heavenly body, the place to look is the Sun.

There are multiple examples in the last 25 years alone. During the great Quebec Blackout of 1989, for instance, more than 9 million people spent a cold autumn night without lights or power. The same storm that blacked out Quebec damaged multi-ton transformers as far away as New Jersey, and Great Britain and caused more than 200 power anomalies across the USA from the eastern seaboard to the Pacific Northwest. A similar series of "Halloween storms" in October 2003 triggered a regional blackout in southern Sweden and may have damaged transformers in South Africa. And eruptions like the July 23 2012 CME demonstrate how even weak solar cycles have the ability to produce historic events. Strong solar storms are not far-fetched and improbable. They have happened in our lifetime.

The problem we face is, ironically, progress. Since the beginning of the Space Age the total length of high-voltage power lines crisscrossing North America has increased nearly tenfold. This has turned power grids into giant antennas for geomagnetically induced currents. With demand for power growing exponentially, modern networks are sprawling, interconnected, and stressed to the limit—a recipe for trouble, according to the a 2008 report of the National Academy of Sciences: "The scale and speed of problems that could occur on [these modern grids] have the potential to impact the power system in ways not previously experienced."

Storms akin to the Carrington event or the Quebec Blackout could cause lasting damage to these modern smart power grids, irreparably damaging transformers and knocking out power for months in areas hundreds to thousands of miles wide. Clean water supplies, financial services, telecommunications and even some aspects of medical care could be crippled.

These dangers are the reason why we can call STEREO a "planetary hazards mission." Although the twin probes were dispatched to do research, they have quickly produced practical benefits, arguably advancing the art and science of space weather forecasting more than any other solar observatory.

As humankind expands into the solar system, STEREO will be remembered as the mission that gave a new broader meaning to the term "planetary hazards." Earth isn't the only world in the crosshairs of the Sun. With STEREO, and follow-up missions like it, we may be able to protect them all.

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Cross-References

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Basics of Solar and Cosmic Radiation and Hazards
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