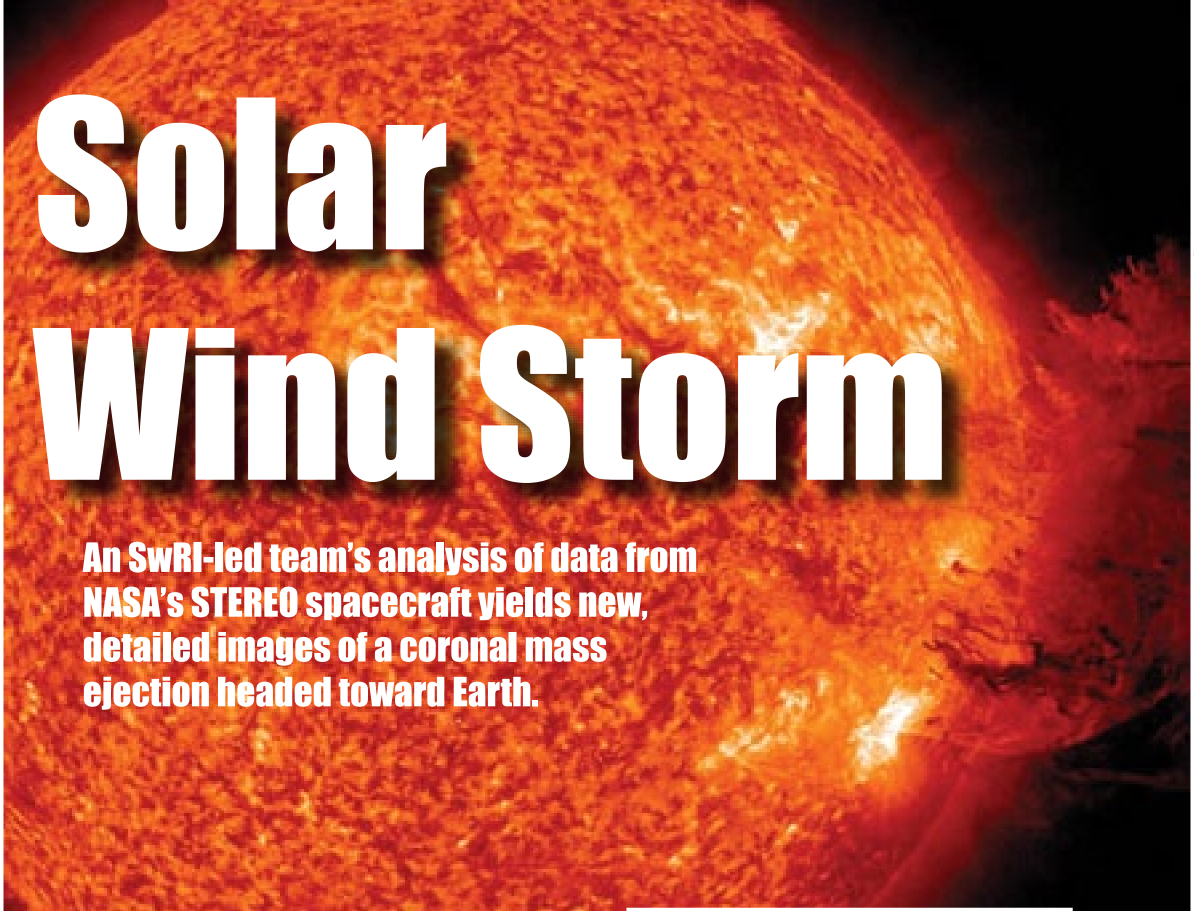
Solar Wind Storm

An SwRI-led team's analysis of data from NASA's STEREO spacecraft yields new, detailed images of a coronal mass ejection headed toward Earth.



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On December 12, 2008, a CME formed in the solar corona and traveled across the void over the next few days until it impacted Earth. By combining images from five different instruments, the SwRI team was able to track it on its earthward journey.

Photo courtesy NASA

By Craig DeForest, Ph.D.

In December 2008, amid a storm of electromagnetic activity, the Sun ejected half a billion tons of protons, electrons and other particles, which rode the solar wind toward Earth at a million miles an hour, impacting the planet's protective magnetic bubble just over three days later.

Unlike earlier Earth-impacting coronal mass ejection (CME) events, this one was observed by heliospheric imaging instruments onboard NASA's Solar Terrestrial Relations Observatory (STEREO) spacecraft, which consists of a pair of nearly identical unmanned observatories launched away from Earth into solar orbit, with one leading and the other trailing.

When a team of scientists led by SwRI's Space Science and Engineering Division developed new image processing techniques, the STEREO images revealed an array of dynamic interactions as the solar wind shifted and changed on its three-day, 93-million-mile journey to Earth, guided by the magnetic field lines that spiral out from the Sun's surface.

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Dr. Craig DeForest is a staff scientist in the Space Studies Department within SwRI's Space Science and Engineering Division. His expertise includes image processing and computer vision, instrument design and construction, solar observation planning and execution, software development and numerical modeling of space weather phenomena. His current research focuses on spaceborne imagery to understand the turbulent, dynamic plasma that fills the solar system.

The newly processed images show, for the first time, how CMEs evolve and gather material as they move through the inner solar system; and how the parts of the CME correspond to their sources in the solar corona. These questions are central to the study of "space weather," or how solar explosions affect Earth life and society, but have remained elusive since CMEs were first discovered four decades ago.

Space weather

When a CME impacts our planet's environment, it is deflected by the Earth's magnetic field and the brunt of the energy and particles is shifted

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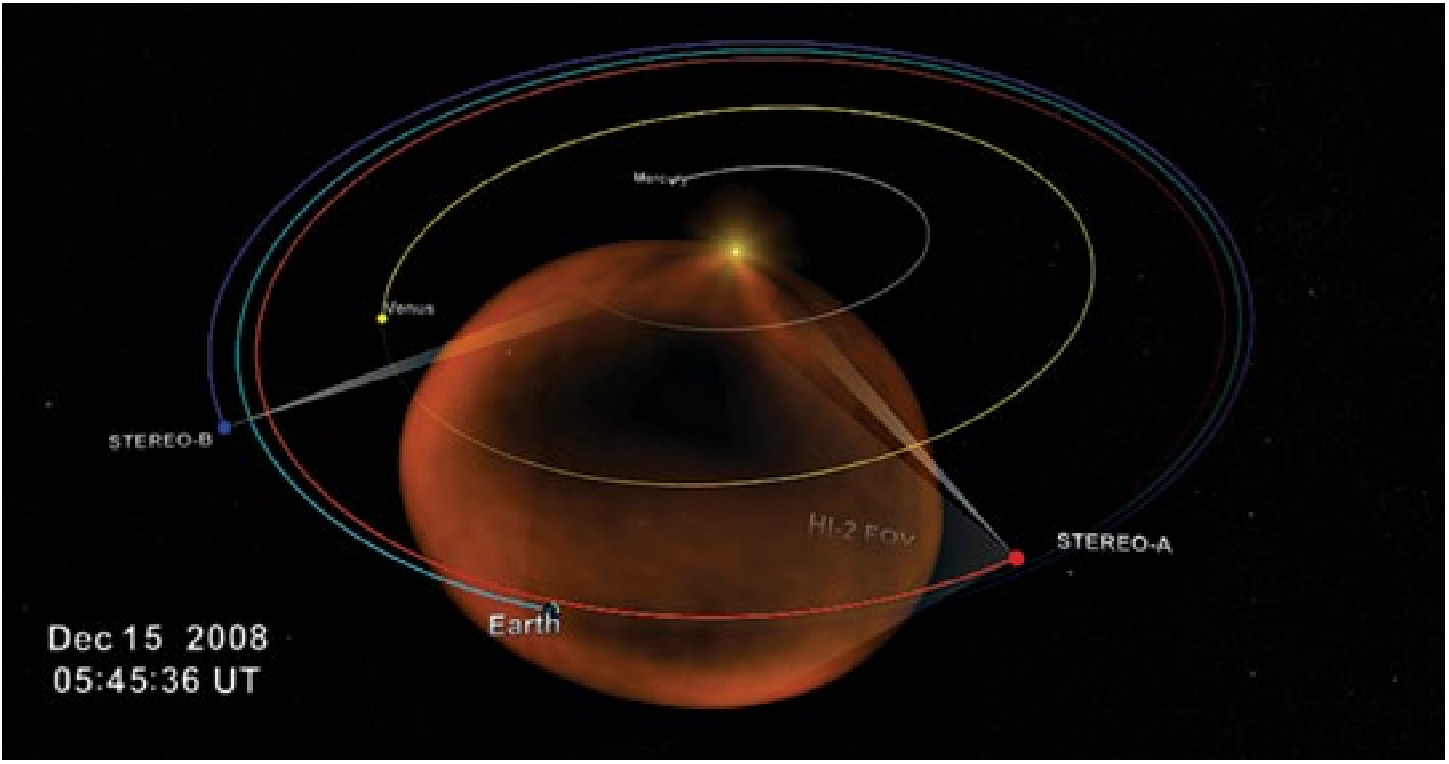

Image courtesy NASA/GSFC science visualization team

The STEREO-A spacecraft is drifting around the Sun ahead of Earth, affording a good vantage point to observe CMEs that leave the Sun and impact Earth.

around our planet. In addition to making compasses work, Earth's magnetic field protects our fragile atmosphere from erosion by CMEs and the solar wind. (Mars was not so lucky; once its magnetic field collapsed eons ago, its atmosphere was gradually swept away.)

Our magnetic force field is not perfect: CME impacts cause "geomagnetic storms" that affect everything from satellites and long-distance radio to municipal power grids and cell phones. CME-related effects on Earth will rise over the next few years as the Sun enters the "maximum activity" phase of the eleven-year sunspot cycle.

Understanding and predicting CME behavior is a major research thrust throughout the world, but it has proven difficult. This is partly because CMEs are very hard to track in interplanetary space, leaving a large gap in our knowledge of how they grow and change as they move through the solar system.

CMEs can be photographed near the Sun using a special camera called a "coronagraph" that blocks the bright Sun itself, revealing sunlight scattered off of free-floating electrons in the Sun's corona. By studying these images of the corona, we have learned much about how CMEs are formed and erupt from the Sun.

Likewise, by measuring CMEs' density and magnetic field *in situ* as they sweep over a space probe such as NASA's ACE spacecraft, we can infer much about the structure of CMEs near Earth. But connecting the *in situ* measurements to the solar images is difficult at best. This is mainly because *in situ* probes measure the solar wind and CME only at a single point. Comparing CME structure between coronagraph images and near-Earth sensor data is something like trying to identify a grown man by comparing baby pictures to microscopic images of his blood cells.

Now, by tracking those features through the image data, scientists can establish definitively what parts of a space weather storm came from which parts of the solar corona, and why.

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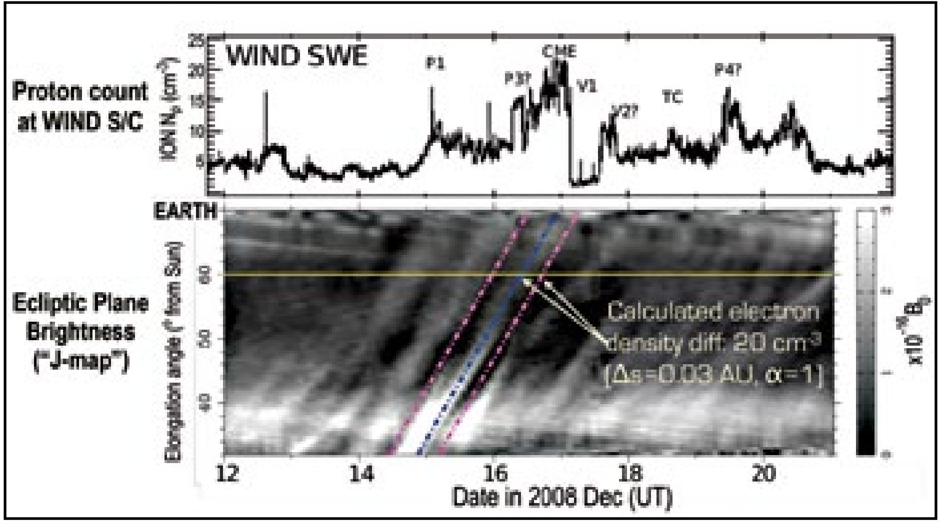

This map of brightness versus time along the outer part of the Earth-Sun line shows how the images of the CME corresponded to density measured in situ *by the Wind spacecraft.*

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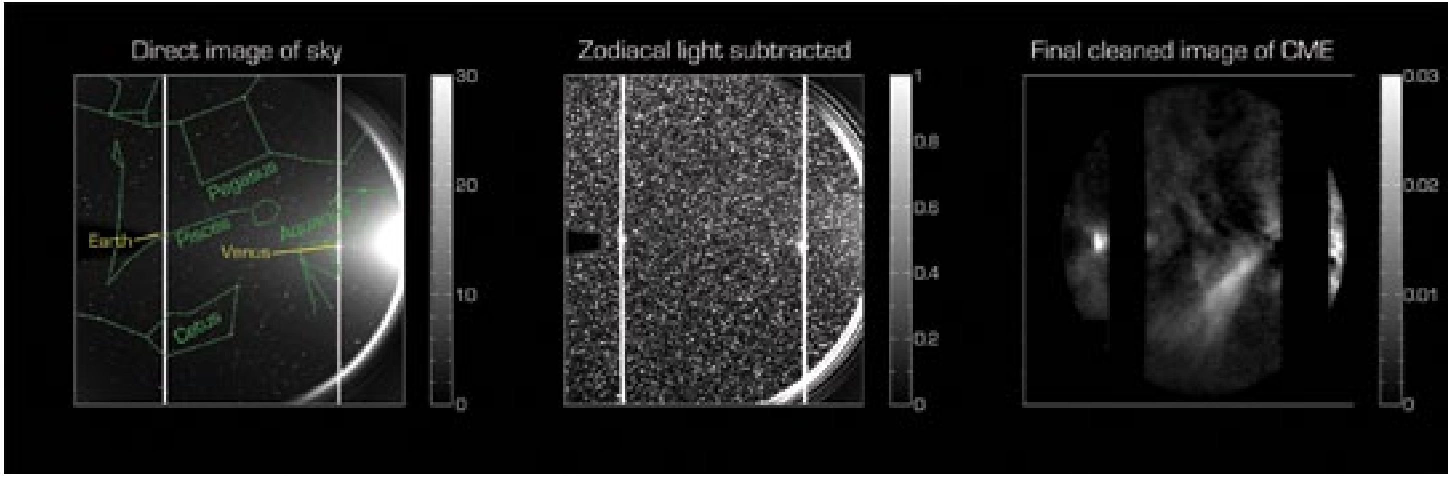

Tracking the CME through STEREO's widest field of view is a challenge because interplanetary plasma clouds are very faint. Even the bright CME (right) is 1,000 times fainter than the starfield (left).

Extracting faint signals

For more than 20 years, ever since the "Helios" spacecraft detected CMEs in interplanetary space using a simple photometer, scientists have known that CMEs can be imaged in flight, but it is extraordinarily difficult because they are so faint. A bright CME in the solar corona can be nearly as bright as the full Moon, but by the time it is halfway to Earth it fades by a factor of one billion in brightness, becoming over a thousand times fainter than the Milky Way.

Imaging the December 2008 CME and the events that followed required a triumph of image processing to separate the faint wisps of material from the background starfield. The SwRI-led team used a six-step process that made use of the starfield itself to measure minute image distortions in the instrument. They co-aligned individual images to better than 1/10 of an image pixel and removed 99.995 percent of the background signal to reveal the moving wisps of solar material.

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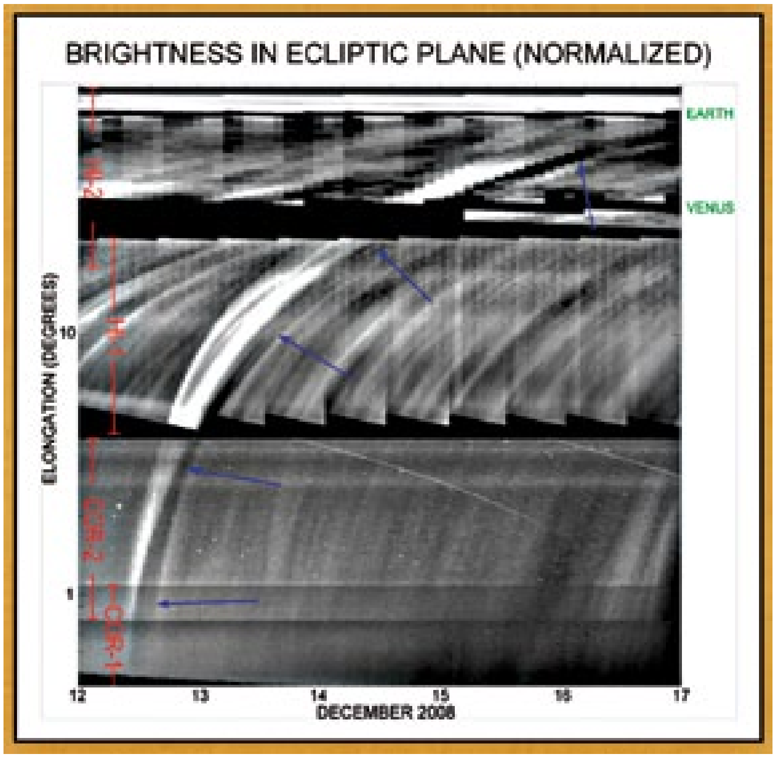

This map of brightness versus time along the Earth-Sun line shows a cut through the CME as it traveled to Earth (bright boomerang curve). The core of the CME is an evacuated magnetic flux rope (dark; blue arrows) that pushed through the solar system, piling up new material like dirt in front of a bulldozer.

CME anatomy

In particular, the team was able to see that most of the material in a CME when it impacts Earth is swept up from solar wind that departed the Sun earlier, only to be overtaken by the fast-moving event. The material is driven by an evacuated bubble of magnetic force — the magnetic "flux rope" that caused the CME in the first place — which continues to push from behind. By the time it impacted Earth, that first CME was over 30 million miles tall, and nine-tenths of the material in it had been scooped up en route.

Further, the flux rope itself is distorted by the drag force of scooping up so much material. Since the strength and orientation of the magnetic field matter as much to space weather as does the amount of entrained material, the SwRI team hopes to learn why some CMEs have strong effects on the Earth while other, equally large, CMEs fizzle.

"I see things … wonderful things!"

When egyptologist Howard Carter peered through a small hole into Tutankhamen's tomb in the 1920s, he is said to have whispered those words to his companions at the dig. Like his faint glimpses of gold and furnishings, the new CME data hint at great things to come.

In quiet periods between CMEs, the team was able to view myriad small, faint clouds of material that seem to correlate with known gusts and fluctuations in the "slow solar wind." That "slow" wind, measured by *in situ* probes, streams out from the Sun through interplanetary space at about 350 km/sec (about 750,000 mph) and its origin and gustiness are mysteries that have stood for nearly 50 years. If the new, puffy clouds are in fact the same as the dense regions we see *in situ*, future studies may be able to resolve those mysteries.

In another big surprise, the new images show many “disconnection events” where magnetic field lines break away from the Sun and depart the solar system entirely, dragging “small” million-mile-high, wishbone-shaped clouds of plasma with them. This process weakens the interplanetary magnetic field (IMF), balancing CMEs and similar eruptive events that build up the IMF. Scientists have long known that there must be some process balancing this injection of magnetic field, and candidate events have been identified by SwRI scientist Dr. David McComas in both *in-situ* data and coronagraphic images. Using the new data, the team has been able to show that these peculiar flying wishbones are key players in determining the strength of the IMF.

Future efforts

The SwRI/National Solar Observatory effort has yielded a new opening into the realm of the heliosphere – the complex, dynamic world that exists in “empty space” between the planets. Like Howard Carter’s small window into a 3,000-year-old time capsule, the first glimpse of the reduced data hints at terrific things to come.

In coming months, the team plans to track several other CME events from early flux rope formation to arrival at Earth in order to identify systematically how variations in the background and in the flux rope itself affect CMEs and the space weather they cause, and even whether all CMEs necessarily have a coherent trailing flux rope.

Even now, while exploiting this rich data set, team members have identified ways to improve observations with a new, optimized instrument. With increased spatial resolution and the ability to measure polarized light, it will become possible for the first time to measure the absolute density of the solar wind across distances of 100 million miles or more, and to measure turbulence, shock fronts, and the mysterious solar energetic particles that shower spacecraft and astronauts.

Funding for this research was provided by the National Science Foundation SHINE Competition, the NASA Heliophysics Program and the National Solar Observatory by the U.S. Air Force under a Memorandum of Agreement. The initial paper, “Observations of Detailed Structure in the Solar Wind at 1 AU with STEREO/HI-2,” by DeForest, I.A. Howard and S.J. Tappin (NSO) was published in the September 1, 2011, issue of the *Astrophysical Journal*, Vol. 738, Issue 1, p-103.

STEREO is part of NASA’s Solar Terrestrial Probes Program in NASA’s Science Mission Directorate in Washington. The program seeks to understand the fundamental physical process of the space environment from the Sun to Earth and other planets.

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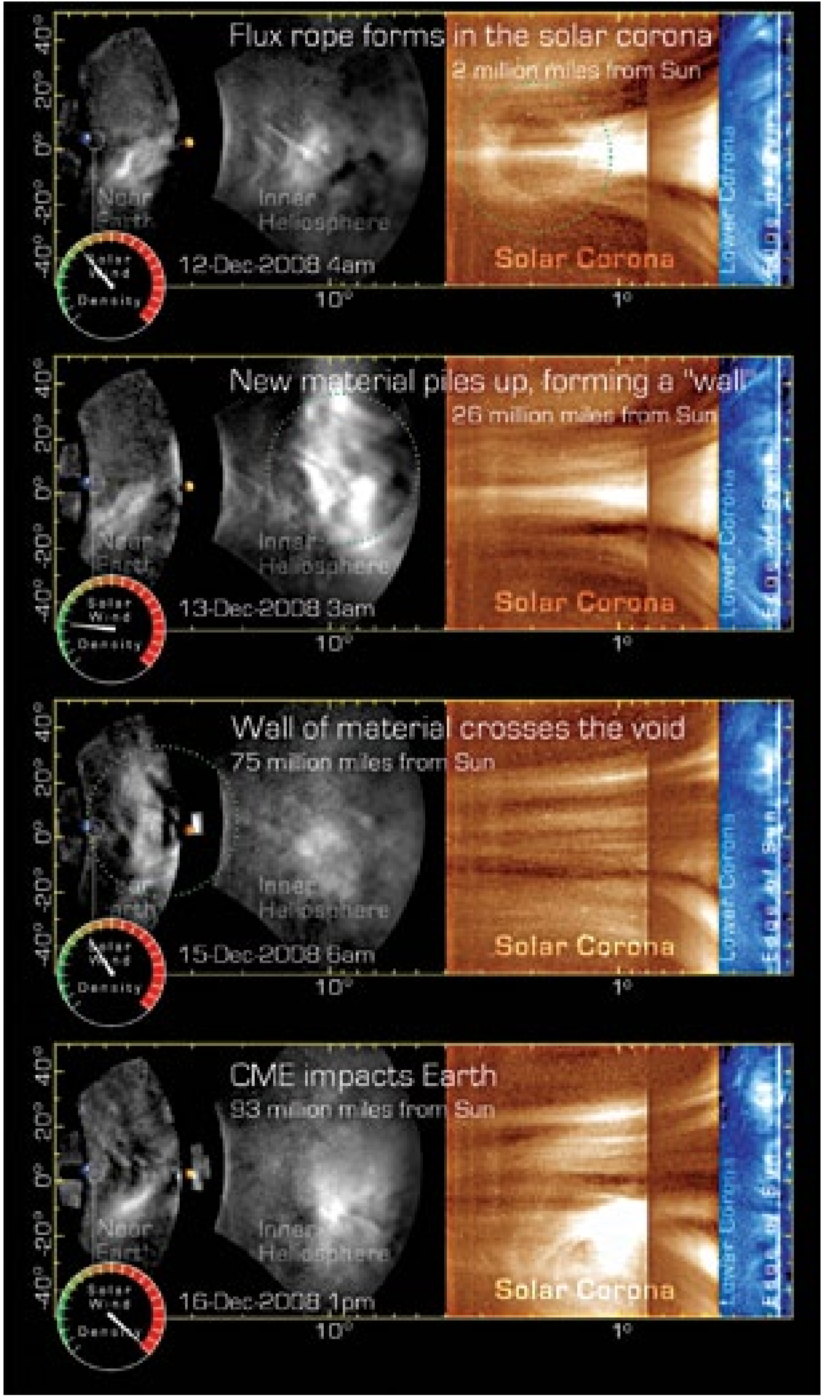

This series of images depicts the evolution of a CME during the time between its formation in the solar corona (top) and its impact at Earth four days later (bottom). The distance scale is logarithmic: The cloud of material grew more than 100 times its linear size while crossing interplanetary space to impact Earth.