Stereoscopic View of the Sun and its Activity in Sight

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The Sun is the central body of our planetary system and has very serious impacts of various kinds on interplanetary space and the environment of planets. Near solar poles, the magnetic field lines are open and solar plasma flows continuously into space, creating fast solar winds, blowing deep into outer regions of the planetary system. At low latitudes, coronal helmet streamers and possibly active regions during the field-line openings are sources of slow solar wind. Streams of accelerated particles, both electrons and atomic nuclei, propagate at various places through interplanetary space. And in addition to these streams of plasma and particles, coronal mass ejections (CMEs) drive plasma clouds and shock waves in various directions through interplanetary space and eventually cause other particle acceleration there. All this creates highly variable and very complex conditions in the space between the Sun and the Earth which we sum up under the term 'space weather'. In the spring this year, NASA will launch the Solar TErrestrial RElations Observatory (STEREO) mission, which will place two spacecrafts into position that will provide a 3-D view of the Sun for the first time. This unique stereo viewing of the Sun will be a landmark development not only for providing more clues to the geometry of CMES, but also alerts for Earth-directed solar flares.

Introduction

The first-ever 3-D stereo-viewing of the Sun and its activity seems to be in sight. The upcoming STEREO, scheduled for launch in Spring 2006 aboard a single Delta II 7925 launch vehicle, is just as unique and groundbreaking as its mission. The lunar swingby will be used to place the twin observatories into their respective orbits. This is the first time this technique has been used to manipulate orbits of more than one spacecraft. Mission designers will use the Moon's gravity to redirect the observatories into their appropriate orbits – something the launch vehicle alone cannot do. Once there, STEREO 'A' will fly ahead of the Earth and STEREO 'B' will fly behind it. STEREO's data will allow scientists to track the buildup and lift-off of magnetic energy from the Sun and the trajectory of Earth-bound coronal mass ejections (CMEs) in 3-D. *Figure* 1 shows a large, eruptive prominence in He II at 304Å, with an image of the Earth added for size comparison. This prominence from 24 July 1999 is particularly large and looping, extending over 35 Earths out from the Sun. Erupting prominences (when Earthward directed) can affect communications, navigation systems, even power grids, while also producing auroras visible in the night skies.

Thousands of millions of tonnes of material are sporadically ejected from the Sun and travel at high speed into interplanetary space (see *Figure* 2). Such transient ejections of

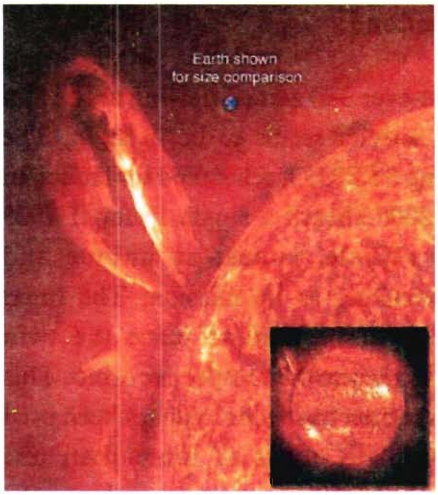

Figure 1. Prominences are loops of magnetic fields with hot gas trapped inside. Sometimes, they erupt and quickly rise off of the Sun as the fields become unstable.
Credit: NASA/SOHO.

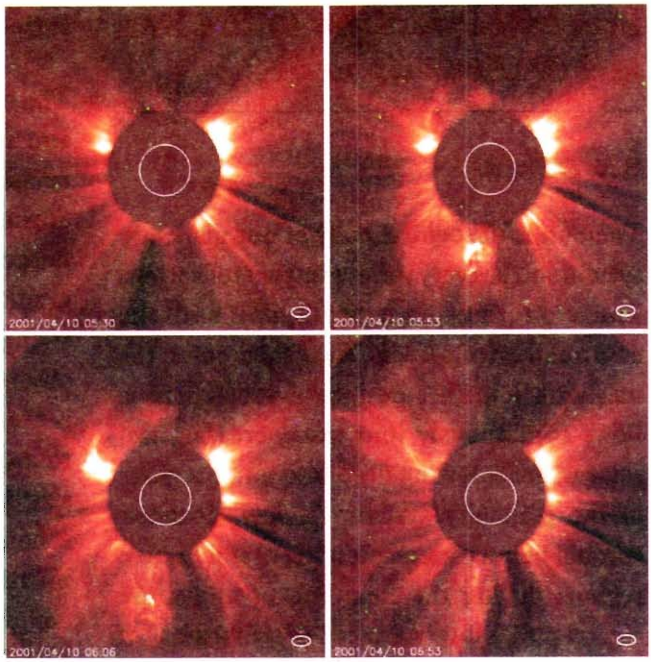

Figure 2. CME blast seen by LASCO C2 – An image sequence over 90 minutes of a large coronal mass ejection on 10 April 2001 associated with an X2.3 flare. A CME blasts a billion tonnes of particles travelling millions of kilometers an hour into space. This CME impacted Earth about 36 hours later and caused a severe geomagnetic storm.
Credit: LASCO/SOHO.

material are called coronal mass ejections (CMEs). They are among the most powerful eruptions in the solar system, but could not be clearly identified until coronagraphs were flown in space, such as OSO-7 and Skylab, in the early 1970s. There is a compelling body of observational evidence to believe that CMEs are launched when solar magnetic fields become strained and suddenly 'snap' to a new configuration, much like a rubber band that has been twisted to the breaking point. These events propel magnetic clouds with a mass of up to 10^{17} gm to speeds up to 2600 km/sec into the heliosphere. The nature and cause of CMEs is a fundamental, yet an unsolved problem. They are often associated with prominence eruptions and/or solar flares.

The Sun – Earth Connection

The Sun and Earth are a connected system. Electromagnetic radiation and electrically-charged particles stream outward from the Sun (the solar wind), envelop the Earth, and interact with the Earth's magnetic field and terrestrial atmosphere creating an adverse environment. The main goal is to understand the changing flow of energy and matter throughout the Sun, heliosphere and planetary environments, thereby to explore the fundamental physical processes of space plasma systems. This ultimately defines the origins and societal impacts of variability in the Sun-Earth connection. There are two different types of events in the solar atmosphere that trigger disturbances in the Earth's environment. They are solar flares and CMEs which are the most powerful particle accelerators in the solar system.

Solar winds are like daily breezes on the Earth – mild and steady. The action of solar flares is through optical flashes, like lightning, and SEP (Solar Energetic Particles) production – much more powerful than solar winds. CMEs are like hurricanes – energetic storms spread over large areas. Flares and CMEs often occur in close context, in particular the big ones. They are both the result of a common underlying cause, a 'magnetic disease' of the Sun. There are CMEs without flares, and there are flares without CMEs, so one cannot be the cause of the other. Flares produce all kinds of electromagnetic radiation that hits and influences the Earth, plus SEPs with energies up to some GeV. They also hit and influence the Earth, within minutes after the solar cause. CMEs drive large-scale shock fronts through the heliosphere which may lead to southward deflection of the interplanetary magnetic field (IMF). The ejecta may contain 'magnetic clouds' that may also have strong southward pointing magnetic fields, required for geomagnetic storms. That depends on the topology of the clouds and the ambient solar wind and is well understood. The only missing piece in the puzzle is our understanding of the conditions that lead to flares and CMEs in the first place.

Energy released in a major solar flare is of the order of 10^{25} Joule which is comparable in strength to 20 million nuclear bombs, each blowing up with an energy of 100 Megatons of TNT (one megaton of TNT is 4.2×10^{22} ergs). A substantial fraction of this energy goes into accelerating electrons and ions to high (relativistic) speeds. These high energy particles go down towards the Sun or out in space, and result in enhanced radio, soft X-ray, hard X-ray and gamma ray radiation. Comparable amount of energy is released in expelling matter during a CME too.

The most dramatic space weather effects, however, are associated with CMEs. These eruptions (CMEs) are sometimes associated with solar flares, and sometimes not, and they now appear to be a primary cause of geomagnetic activity. The primary signature of CMEs in ultraviolet and X-ray images is the creation of post-flare loop systems following the eruption of CMEs. Observations from Yohkoh in X-rays and from SOHO and TRACE in ultraviolet light reveal very extensive arcades associated with CMEs. An opening of magnetic field at the base of CME involves a very extensive region on the Sun. When opening of magnetic field avoids any active region, we do not see any flare. However, if it extends into an active region, the subsequently closing field lines are seen as post flare loops of an eruptive flare (see *Figure* 3).

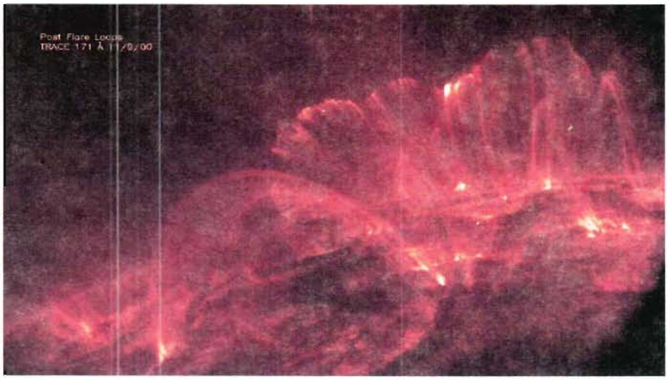

Figure 3. Post-flare loops observed in the Fe IX 171 Angstrom ultraviolet line by TRACE (Transition Region and Coronal Explorer) spacecraft on 9 November 2000.
Credit:TRACE-NASA.

CMEs' Observations

CMEs have been studied primarily from observations using ground-based and space-borne coronagraphs. Observation and interpretation of these events have continuously been carried out with the LASCO (Large Angle and Spectrometric Coronagraph) instrument on the SOHO (Solar and Heliospheric Observatory) spacecraft since its launch on 2 December 1995. SOHO is located at the L1 Lagrangian point (the point 1.5 million kilometers away from us at which gravitational pull of the Earth balances that of the Sun). LASCO provides CME images of excellent quality, and reveals a large complexity and diversity of forms. The major limitation of CME observations to date has been a lack of three-dimensional structure and trajectory measurements. Speed and direction measurements would allow more accurate prediction of CME impacts, which would allow better planning of protective measures, such as altitude adjustment and astronaut shielding. If the basic desire is to see the front of a CME heading towards the Earth, we just need observations out of the Sun-Earth line, i.e., STEREO (see the artist's concept of the twin STEREO observatories, *Figure* 4). Three-dimensional measurements, however, would yield better insights in CME generation and propagation as well as permit additional tests of CME dynamical models.

Theory holds that coronal loops act like a net to restrain energized magnetic fields that are trying to rise. Constantly in motion, loops can merge in a process called magnetic reconnection, which rips the net. Barrelling through the slower solar wind, a CME creates a shock wave that can boost its charged plasma and radiation to ultra-high energies. It takes one to four days for a CME to reach us. SOHO and other satellites can detect its liftoff, but not until about an hour before the impact can we measure how bad it will be. In the worst case, a CME carries a southward magnetic field orientation, the opposite of the Earth's. Such a CME not only compresses our protective magnetosphere (exposing satellites to particles), it also links to our dayside magnetic field and peels back field lines. Then, at the nightside tail, Earth's lines reconnect, driving trillions of watts of power

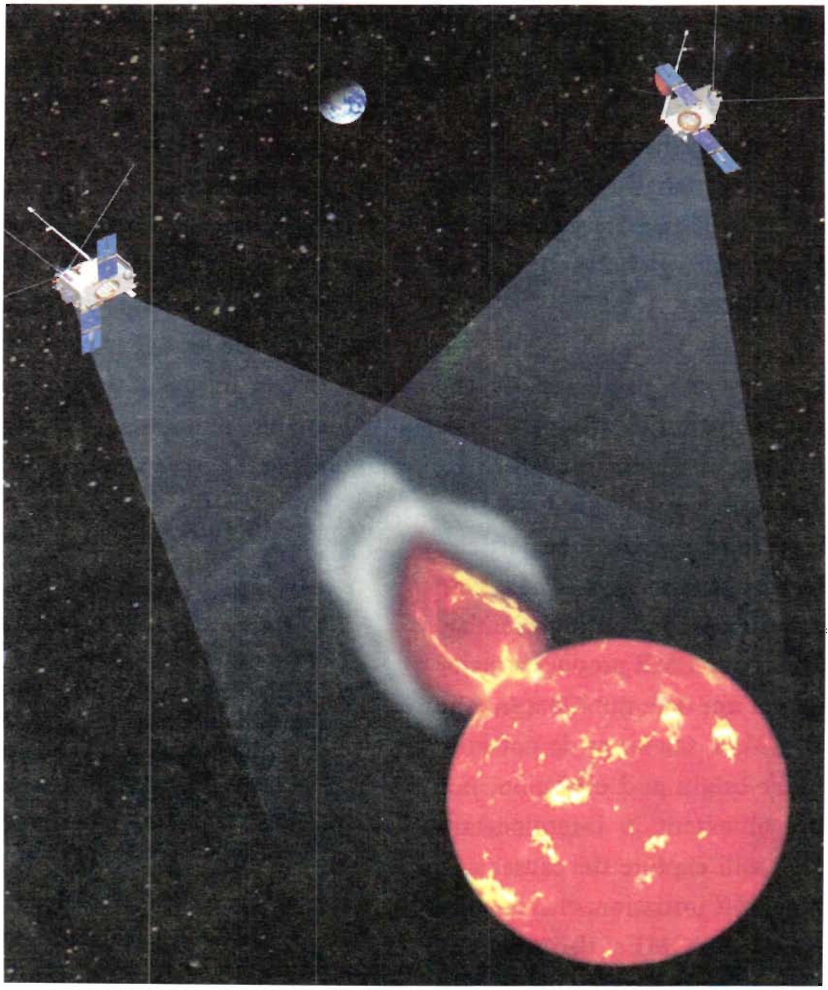

Figure 4. Artist's concept of the twin STEREO Observatories studying the Sun. *Credit : SOHO, NASA/ESA.*

into the upper atmosphere. What explains flares, and the CMEs that are responsible for electrical tempests on Earth? How can these storms be predicted? We can now record these storms leaving the Sun in a way we never could before with SOHO. We can also predict with 80% accuracy whether or not they will hit the Earth. The missing piece however, is our understanding of the conditions that lead to CMEs in the first place.

Stereo View of Stormy Space Weather

In terms of space weather forecasting, we are where weather forecasters were in 1950s – they did not see hurricanes until the rain clouds were right above them. Today we can see storms leaving the Sun, but we have to make guesses and use models to figure out if and when it will impact the Earth. It is like seeing the stuff with one eye which results in losing the ability to judge perspective and depth. We are basically looking at the Sun with one eye. With STEREO, we are going to have the ability to gain the extra dimension, depth perception, which we did not have before. STEREO will use stereoscopic (3-D) vision to construct a global picture of the Sun and its influences.

Here on Earth we are protected by the atmosphere and magnetic fields from the Sun's radiation. But when we send astronauts to the Moon and beyond, we will need a better understanding of the dangerous solar particles accelerated by shock waves from CMEs. One of the biggest mysteries confronting scientists today is why does one CME produce a major storm and another one does not ? Despite the importance of CMEs, scientists do not fully understand their origin and evolution, nor their structure or extent in interplanetary space. STEREO will explore the causes and mechanisms of CME initiation, characterize the propagation of CMEs through the heliosphere, discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium, and improve the determination of the structure of the ambient solar wind. During its 2-year life, STEREO will provide a new perspective on the Sun by taking stereoscopic measurements of the Sun and CMEs. Each of the two observatories carries a complement of imaging, remote-sensing and particle and field instruments. STEREO is the first mission to image CMEs continuously in three dimension from the Sun and Earth. And its unique stereoscopic images of the structure of CMEs will enable scientists to determine their fundamental nature and origin.

Suggested Reading

[1] Z. Svestka, Solar Activity, in *Dynamic Sun*, B N Dwivediv (ed.), Cambridge University Press, pp. 238-261, 2003.

[2] B Fleck and C U Keller, Solar Observing Facilities, in *Dynamic Sun*, B N Dwivedi (ed.), Cambridge University Press, pp. 403-433, 2003.

[3] STEREO website: http://stereo.gsfc.nasa.gov

[4] http://www.nasa.gov/mission_pages/stereo/main/index.html

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