

Solar and Heliospheric Observatory (SOHO) (1995)

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Abstract

SOHO is the most comprehensive space mission ever devoted to the study of the Sun and its nearby cosmic environment known as the heliosphere. It was launched in December 1995 and is currently funded at least through the end of 2016. SOHO's twelve instruments observe and measure structures and processes occurring inside as well as outside the Sun, and which reach well beyond Earth's orbit into the heliosphere. While designed to study the "quiet" Sun, the new capabilities and combination of several SOHO instruments have revolutionized space weather research. This article gives a brief mission overview, summarizes selected highlight results, and describes SOHO's contributions to space weather research. These include coterminous EUV imaging of activity in the Sun's corona and white light imaging of coronal mass ejections in the extended corona, magnetometry in the Sun's atmosphere, imaging of far side activity, measurements to predict solar proton storms, and monitoring solar wind plasma at the L1 Lagrangian point, 1.5 million kilometers upstream of Earth.

Keywords

Sun – Heliosphere – CMEs – Space Weather

Introduction

SOHO, the Solar and Heliospheric Observatory, is a mission of international cooperation between ESA and NASA to study the Sun, from its deep core to the outer corona, the solar wind, and solar energetic particles. Together with *Cluster*, it forms the Solar-Terrestrial Science Program (STSP), the first "cornerstone" of ESA's long-term programme known as "Space Science – Horizon 2000". STSP, in turn, was part of the International Solar-Terrestrial Physics Program (ISTP), a cooperative scientific satellite project of NASA, ESA, and ISAS which aimed at gaining improved understanding of the physics of solar-terrestrial relations by coordinated, simultaneous investigations of the Sun-Earth space environment over an extended period of time.

SOHO was designed to answer the following three fundamental questions about the Sun: What is the structure and dynamics of the solar interior? Why does the solar corona exist and how is it heated? Where is the solar wind produced and how is it accelerated?

In the following paragraphs we describe the “original” SOHO mission as it has been operated for over 15 years until the spring of 2011. Following the launch of NASA’s Solar Dynamics Observatory (SDO), which carries vastly improved versions of two of SOHO’s primary instruments, and in response to budget pressures, SOHO operations have been significantly reduced in recent years. A brief summary of the current status of SOHO and anticipated changes is also given. Detailed descriptions of all twelve instruments, the science operations and data products, as well as a complete mission overview, can be found in Fleck et al. (1995).

We will start with an overview of the mission (spacecraft, orbit, payload, operations), followed by a short summary of some of SOHO’s main scientific accomplishments. We then discuss SOHO’s contributions to space weather research, which include the combination of coronal imaging in the EUV and white-light imaging of the extended corona, continuous mapping of the Sun’s magnetic field, imaging of active regions on the far side of the Sun, predicting the arrival of solar energetic particles (SEPs) based on measurements of energetic electrons, and *in situ* measurements of shock fronts of coronal mass ejections (CMEs) as they sweep over the Lagrangian Point L1.

Mission Overview

Spacecraft

SOHO is a three-axis stabilized spacecraft that constantly faces the Sun. Its design is based on a modular concept with two main elements: the payload module, housing the 12 instrument packages, and the service module, providing essentials such as thrusters, power and communications. SOHO’s mass at launch was 1850 kg, its dimensions are 4.3 x 2.7 x 3.7 m³ (9.5 m with solar arrays deployed). Design life was 2 years, with consumables (hydrazine) onboard for another 4 years. The current hydrazine reserves in fact are sufficient for several more decades of normal operation and the solar arrays should provide sufficient energy at least until the end of 2018. SOHO has excellent pointing performance, with errors typically smaller than 1 arcsec.

SOHO was designed, assembled and tested by a consortium of European space companies led by prime contractor Matra Marconi Space (now Airbus Defense & Space) under ESA management. NASA contributed the Atlas IIAS rocket on which SOHO was launched and is responsible for telecommunications (using NASA’s Deep Space Network, DSN) and daily operations, while ESA has overall responsibility for the mission. The focal point for spacecraft operations, science planning, and instrument operations is NASA’s Goddard Space Flight Center.

Orbit

SOHO was launched on 2 December 1995 and inserted into a halo orbit around the L1 Lagrangian point in February 1996. There the combined gravity of Earth and Sun keep SOHO in an orbit locked to the Earth-Sun line. Nominal science operations started on 2 May 1996. The L1 halo orbit was chosen as it allows: a) uninterrupted observations of our star, b) sampling of the solar wind and energetic particles outside Earth’s magnetosphere, and c) extremely good observing conditions for the detection of solar velocity oscillations with high accuracy and sensitivity by minimizing radial velocity variations.

Payload

The payload consists of a set of twelve complementary instruments, developed and furnished by twelve international Principal Investigator (PI)-led consortia involving 39 institutes from fifteen countries. Nine consortia are led by European PIs, the remaining three by US PIs. The payload weighs about 640 kg and consumes 450 W.

SOHO's twelve instruments, which represent the most comprehensive set of solar and heliospheric instruments ever developed and carried on the same platform, are listed in Table 1. The payload includes three helioseismology and solar irradiance instruments (GOLF, VIRGO, MDI) that have provided unique data for the study of the structure and dynamics of the solar interior, from the very deep core to the outermost layers of the convection zone; a set of five complementary remote sensing instruments, consisting of EUV and UV imagers, spectrographs and coronagraphs (SUMER, CDS, EIT, UVCS, LASCO, SWAN), that have given us our first comprehensive view of the outer solar atmosphere and corona; and three *in-situ* instruments (CELIAS, COSTEP, ERNE) making measurements of the composition and energy of the solar wind and charged energetic particles.

Table 1: Instruments on SOHO.

Instrument	Principal Investigator
Global Oscillations at Low Frequency (GOLF) Na-vapour resonant scattering cell to measure global Sun velocity oscillations	P. Boumier, IAS, F
Variability of solar IRradiance and Variability (VIRGO) Active cavity radiometers and sun photometers for total and spectral irradiance	C. Fröhlich, PMOD/WRC, CH
Michelson Doppler Imager (MDI)* Fourier tachometer to measure velocity oscillation up to $l = 4500$	P. Scherrer, Stanford. Univ., USA
Solar UV Measurements of Emitted Radiation (SUMER) Normal incidence spectrometer; 500-1600 Å; spectral res. 20000-40000	W. Curdt, MPS, D
Coronal Diagnostic Spectrometer (CDS) Normal and grazing incidence spectrometers, 150-800 Å	A. Fludra, RAL, UK
Extreme-ultraviolet Imaging Telescope (EIT) Full disk images (1024x1024) in He II, Fe IX, Fe XII, Fe XV	F. Auchère, IAS, F
UltraViolet Coronagraph Spectrometer (UVCS)* UV lines (Ly α , O VI, etc.) in extended corona (1.3 to 3 R_{\odot})	L. Strachan, SAO, USA
Large Angle and Spectrometric COronagraph (LASCO) Overlapping externally occulted coronagraphs: 2-30 R_{\odot}	R. Howard, NRL, USA
Solar Wind ANisotropies (SWAN) Scanning telescopes operating in Ly α to measure solar wind mass flux	E. Quémerais, LATMOS, F
Charge, Element and Isotope Analysis System (CELIAS) Electrostatic deflection, time-of-flight measurements, solid state detectors	R. Wimmer-Schweingruber, Univ. Kiel, D
Comprehensive SupraThermal Energetic Particle analyser (COSTEP)	B. Heber, Univ. Kiel, D

p, He: 0.04-53 MeV/n, e: 0;04-5 MeV; solid state and plastic scintillator detec.	
Energetic and Relativistic Nuclei and Electron experiment (ERNE) p-Ni: 1.4-540 MeV/n, e: 5-60 MeV; solid state and plastic scintillator detectors	E. Valtonen, Univ. Turku, SF

* no longer operated

Cleanliness and Calibration

UV instruments on earlier solar space missions have sometimes shown rather strong drops in responsivity after being exposed to solar radiation in space, due to polymerization of molecular contaminants. To avoid the danger of permanent degradation of the throughput of the SOHO instruments and to protect the instruments observing the corona against particulate contamination, cleanliness was recognized early in the development of SOHO as a prime concern. As a consequence, a very stringent cleanliness program was implemented in order to assure clean environmental conditions for the sensitive experiments. Considerable effort went into making the radiometric response of the SOHO UV and EUV instruments directly traceable to a primary laboratory standard, namely synchrotron radiation produced by storage rings. Because of unavoidable detector aging, a rigorous in-flight intercalibration program was implemented to monitor and maintain the calibration of instruments in orbit. For some instruments, that included suborbital intercalibration rocket flights. For details about SOHO's cleanliness and calibration program see Pauluhn et al. (2002).

Operations

The SOHO Experimenters' Operations Facility (EOF), located at NASA's Goddard Space Flight Center (GSFC), served as the focal point for mission science planning and instrument operations. There the experiment teams received real-time and playback telemetry, processed those data to determine instrument commands, and sent commands directly from their workstations through the ground system to their instruments, both in near real-time and on a delayed execution basis. From the outset SOHO was conceived as an integrated package of complementary instruments, being once described as an "object-oriented", rather than an "instrument-oriented" mission. There was therefore great emphasis on coordinated observations. Internally, this was facilitated through a nested scheme of planning meetings (monthly, weekly, daily), and externally through close coordination and data exchange for special campaigns and collaborations with other space missions and ground-based observatories over the Internet. In response to budget pressures and the increased feasibility of remote science operations *via* the Internet, the SOHO EOF and the SOHO Experimenters' Analysis Facility (EAF) at GSFC were closed at the end of November 2010. Most remote sensing instruments are now being operated remotely from the PI home institutions.

The SOHO spacecraft was originally designed for 24/7 manual operations. Starting in late 2006, SOHO engineers began an in-house reengineering effort to automate the spacecraft operations in an effort to reduce operations cost. This required the development of new ground software (pass generator, anomaly detection and notification) as well as modifications of the Central On-Board Software. Since September 2008, all DSN contacts (except non-routine passes such as station keeping and momentum management manoeuvres) are automated.

Recent mission changes

NASA's Solar Dynamics Observatory (SDO – see Chapter on SDO in this volume), which was launched on 11 February 2010, carries vastly improved versions of SOHO's MDI and EIT instruments, as well as an EUV irradiance monitor. After the cross-calibration of EIT with SDO/AIA at the end of July 2010 the EIT image cadence has been reduced to two synoptic sets of images in all four wavelengths each day to track detector behavior and to maintain the uniform data set, spanning now over one and a half solar cycles. The telemetry bandwidth that had been used by EIT is now being used by LASCO to improve the cadence of its observations of the fastest CMEs.

After the successful completion of the cross-calibration with SDO/HMI, MDI was commanded to stop taking science data on 12 April 2011 at 23:22:31UT. MDI operated exceptionally well for more than 15 years and has produced data that form the basis of over 1700 papers in the refereed literature.

On 23 January 2013, 17 years after the Ultraviolet Coronagraph Spectrometer (UVCS) obtained its first ultraviolet spectra of the extended solar corona, it was commanded to end operations because the detectors were no longer capable of producing scientifically meaningful observations.

The SUMER detectors are very close to end of life and NASA's Interface Region Imaging Spectrograph (IRIS), which was successfully launched on 27 June 2013, has vastly improved performance characteristics compared to SUMER. Following another cross-calibration campaign in the spring of 2014, SUMER science operations will be terminated in 2014.

CDS, which has been superseded to a large degree by Hinode/EIS, will be commanded to end operations in the second quarter of 2014 because of budget constraints in the UK.

All other instruments (VIRGO, GOLF, LASCO, SWAN, CELIAS, COSTEP, ERNE) are fully functional and continue to make unique and important contributions to the "Heliophysics System Observatory".

Summary of Key Findings

SOHO has provided an unparalleled breadth and depth of information about the Sun, from its interior, through the hot and dynamic atmosphere, out to the solar wind and its interaction with the interstellar medium (e.g. Fleck et al. 2000, 2006). SOHO's findings have been documented in an impressive and growing body of scientific literature and popular articles. It is impossible to do justice to the 4700-plus articles published in the refereed literature (as of end of 2013) and an even greater number in conference proceedings and other publications, representing the work of more than 3200 scientists worldwide. Here, we can only briefly summarize a few selected results based on data from SOHO. In the following section, we will discuss space-weather related results in some more detail.

SOHO provided the first-ever images of structures and flows below the Sun's surface and of activity on the far side of the Sun. Analysis of the helioseismology data from SOHO has shed new light on a number of structural and dynamic phenomena in the solar interior, such as the absence of differential rotation in the radiative zone, subsurface zonal and meridional flows, sub-convection zone mixing, a very slow polar rotation, and shear zones in the solar rotation rate just below the surface of the Sun and at the tachocline (transition between radiative and

convection zone). SOHO discovered sunquakes and eliminated uncertainties in the internal structure of the Sun as a possible explanation for the “neutrino problem”. It allowed the detection of sunspots in the deep interior of the Sun 1-2 days before they appeared at the solar surface.

The ultraviolet imagers and spectrometers on SOHO have revealed an extremely dynamic solar atmosphere where plasma flows play an important role. They discovered new dynamic solar phenomena such as coronal waves and solar tornadoes and provided evidence for upward transfer of magnetic energy from the surface to the corona through a “magnetic carpet” (a weave of magnetic loops extending above the Sun’s surface). SOHO measured the acceleration profiles of both the slow and fast solar wind and identified the source regions of the fast solar wind. SOHO discovered that heavy solar wind ions in coronal holes both flow faster and are heated hundreds of times more strongly than protons and electrons, and that they have highly anisotropic temperatures reaching hundreds of millions degrees Kelvin in the direction perpendicular to the magnetic field.

SOHO revolutionized our understanding of solar-terrestrial relations and dramatically boosted space weather forecasting capabilities by providing, in a near-continuous stream, a comprehensive suite of images covering the dynamic atmosphere and extended corona. SOHO has measured and characterized over 20,000 CMEs. CMEs are the most energetic eruptions on the Sun and the major driver of space weather. They are responsible for all of the largest solar energetic particle events in the heliosphere and are the primary cause of major geomagnetic storms.

SOHO has measured for over 1 ½ solar cycles the total solar irradiance (the “solar constant”), spectral irradiance as well as variations in the extreme ultraviolet flux which are important for the understanding of the impact of solar variability on Earth’s climate. High-precision visible light measurements of the Sun’s shape and brightness during two special 360° roll maneuvers of the SOHO spacecraft have produced the most precise determination of solar oblateness.

Besides watching the Sun, SOHO has become the most prolific discoverer of comets in astronomical history: as of late 2013, over 2500 comets have been found by SOHO, most of them by amateurs accessing SOHO near-real-time data via the Internet. Moreover, UVCS provided plasma diagnostic measurements of many of the sungrazing comets from both planned and serendipitous observations.

SOHO’s Contributions to Space Weather Research

CMEs and Space Weather before SOHO

Coronal Mass Ejections, or CMEs, are eruptions of magnetized plasma from the Sun's atmosphere (see e.g. Kunow et al. 2006). They were originally detected in the early 1970s when specialized telescopes called *coronagraphs* were first flown in space. Coronagraphs produce artificial eclipses of the Sun, occulting light from the million-times brighter solar disk so that the extended atmosphere, or corona, can be seen. As such, these telescopes are critically susceptible to stray light in order to detect the corona. In Figure 1 one can see a typical coronagraph series of images of a CME taken by LASCO C2. For a recent review of the observational aspects of CMEs see Webb and Howard (2012), for models of CMEs Chen (2011).

Fig. 1: CME eruption in white light as observed by SOHO/LASCO C2. The relative size and location of the Sun can be seen by the inset cotemporaneous EIT image on the LASCO occulting disk. Two bright coronal streamers can be seen at the 4 and 7 o'clock position extending from underneath the LASCO occulting disk. The CME appears in the south-west streamer and proceeds to disrupt it (upper right frame at 10:29). Note the distinct magnetic flux rope structure which can be seen as a series of almost concentric windings in the 11:27 image (lower left). The CME is associated with a bright prominence that trails behind the flux rope.

CMEs striking Earth's magnetosphere are known to be the cause of the most significant geomagnetic storms. They also drive magneto-hydrodynamic shocks that accelerate energetic particles and fill the heliosphere with energized particles. At the end of the 1980's two developments highlighted the importance of understanding, or at least predicting, CMEs. The first was the collapse of the Hydro-Quebec power grid in 1989 due to a severe geomagnetic storm. This encouraged policy-makers in the United States to formulate a cross-Agency National Space Weather Plan to coordinate resources and undertake new programs, such as NASA's Living With a Star program. The second development was a shift in the research community from a focus on solar flares to CMEs as primarily important for solar-terrestrial physics. These developments set the stage for two spacebased platforms that followed in the second half of the 1990's that revolutionized the curiosity-driven science of solar and space physics into the applied science called *space weather*. Those two spacecraft were NASA's Advanced Composition Explorer (ACE) and SOHO. ACE also resides at the Lagrangian L1 point, and it was designed to send a continuous stream of highly-compressed telemetry of *in situ* measurements of solar wind parameters just upstream of Earth's magnetosphere that were relevant to the short-term (30-60 minute) prediction of the onset of geomagnetic activity (see Chapter on ACE in this volume). For broader accounts of *space weather* see Schwenn (2006), Bothmer and Daglis (2007), Schrijver and Siscoe (2009), or Song et al. (2001).

Significant questions about CMEs remained unanswered prior to the launch of SOHO: What was their relationship to other forms of solar activity, particularly in terms of timing and causality? Although the morphology of some CMEs appeared to be a three-part-structure (bright leading edge, dark trailing cavity, and bright prominence material trailing), what factors determined the variations of that form? Finally, there was the dispute about the interpretation (indeed, even the existence) of "halo" CMEs that surrounded the occulting disk and appeared to be directed toward the observer – could those events presage geomagnetic storms?

CMEs and Space Weather after SOHO

The questions posed above were answered within the first year of operation of SOHO's LASCO and EIT, primarily due to significant improvements in these instruments compared to earlier ones. The dynamic range of LASCO's CCD detectors was orders of magnitude larger than vidicon tubes used in previous coronagraphs, and the location of SOHO at L1 provided a greatly reduced and more stable stray-light background so that fainter CMEs could be detected and tracked than ever before. Earlier coronagraphs on Skylab, SMM, and P78-1 were in low-Earth, low inclination orbits with 15 day-night transitions every 24 hours. Two problems arose from this: a) an approximately 40% loss of coverage, and b) thermal distortions which resulted in a large and continuously-changing stray-light background because of small changes in the sensitive alignment of the optical benches.

The relatively rapid (e.g. 10-20 minutes) cadence of EIT images allowed many CMEs to be unambiguously associated with various forms of activity in the low corona for the first time. Of particular interest were the "EIT waves" that appeared to map the expansion of the CME across the solar surface (Fig. 2). Also, the intentional overlap (or nesting) of fields-of-view between EIT and LASCO's C1-C2-C3, meant that events could be tracked from their initiation in the low corona out to the extent of the C3 field of view. The superior imaging capability of LASCO revealed that the three-part-structure seen in many CMEs appeared to be a magnetic flux rope, thus giving physical insight to the myriad of morphologies that had been reported earlier (cf. Fig. 1). This understanding was critical to the subsequent physics-based modeling of the initiation and propagation of CMEs, and many of our current space weather forecasting tools are now built on this fact.

Fig. 2: A time series of running difference images spanning 34 minutes in the Fe XII 195 Å channel of SOHO/EIT. Centered on a flaring active region just to the north on the central meridian one can see a nearly circular disturbance (the "EIT wave") as it propagates across the disk. The wave appears as the patchy bright features, leaving a region of reduced emission behind (dimming region).

The existence of halo CMEs (St. Cyr 2005) was confirmed because of the aforementioned improvements in detecting faint events. The combination of LASCO and EIT allowed observers to be able to distinguish between halo CMEs directed toward Earth and those originating on the far side. During the development of SOHO, as was evident from their original allocation of onboard resources, LASCO and EIT were considered "context" instruments for the spectrometric telescopes. However, during the first year of SOHO's operation, it became clear that the significant improvements in image quality, combined with real-time return of LASCO and EIT images (almost 20 hours per day) would define the "gold standard" for mid-range (1-3 day) space weather forecasting (Fig. 3). SOHO operations personnel established a protocol to contact NOAA's Space Environment Center (now Space Weather Prediction Center) with timely information on the appearance of Earth-directed CMEs. Many researchers then began using the LASCO and EIT data in various techniques, and combined with different auxiliary observations, to predict the arrival time of CMEs and interplanetary shocks. In 1998, additional telemetry was allocated to LASCO and EIT to improve the cadence of observations, and the mid-term forecasting capabilities were significantly expanded.

Fig. 3: Top left: MDI visible light image of the solar disk taken on 28 October 2003, where multiple large active regions can be seen. Top right: MDI magnetogram on the same day, illustrating the magnetic complexity of these active regions. Lower left: EIT Fe XII 195 Å image at the time of the X17 x-ray flare, seen as the bright emission just south close to the central meridian. The linear horizontal feature is an artifact due to saturation of the CCD detector. Lower right: LASCO C3 image at minutes after the flare (11:30 UT) where a halo CME completely surrounding the occulting disk is visible. The flare location and the existence of the halo CME was a clear indication that the event was heading towards Earth.

[Additional scientific understanding of CMEs from SOHO](#)

Observers have continued to populate the LASCO CME catalogue with information about the appearance, size, speed, and mass of individual events, now numbering more than 20,000, and

researchers internationally compare these with their own observations of associated phenomena. With the growing size of that database and the launch of STEREO with multiple coronagraphs, some researchers began experimenting with the automated detection and measurement of CMEs. The algorithms were developed using archival data, and that has become a veritable cottage industry in recent years with almost a dozen technical approaches appearing to have some levels of success.

Another SOHO instrument has also provided significant new insights into CME research. UVCS was able to obtain spectroscopic observations of over 1000 CMEs imaged by LASCO, during both planned and serendipitous observation. For the first time, UV emission lines of the pre- and post-eruption coronal plasma, as well as the CME itself, have been observed, and diagnostics such as the line-of-sight velocity, density, composition, ionization state, and temperature allow researchers to link the CME onset characteristics to the coronal white-light images. Using the UVCS observations, the thermal history of the ejected plasma can be constrained, and realistic three-dimensional models of CMEs can be compared with simulations. Numerous shock waves and current sheets associated with CMEs have also been observed by UVCS, and this has allowed comparison of plasma densities and compression factors with radio bursts.

The future of CME research

The heliophysics community wants to understand the initiation of CMEs, their propagation into the heliosphere, their impact at Earth and throughout the solar system, and the large-scale structure of the corona through a full magnetic cycle. The success of SOHO LASCO in advancing the understanding of CMEs, combined with the inherent limitations of a single vantage point in tracking events to Earth, led directly to the development of the STEREO mission (see Chapter on STEREO in this volume). The success of combining EIT and LASCO, as well as the high cadence/high resolution EUV imaging from the TRACE Small Explorer mission (1998 – 2010), led to the development of SDO. In order to further our understanding and modeling of the initiation of CMEs, researchers are using high cadence EUV and vector magnetic field information from SDO and combining them with white light coronal data from SOHO/LASCO. Reconstructions of the propagation of CMEs into the heliosphere can only be modeled accurately using as many viewpoints as possible, for example the two STEREO spacecraft and SOHO. Only LASCO provides a continuous record of the large-scale corona over more than an entire solar cycle from one viewpoint.

MDI magnetic field maps

The Sun's magnetic field is the driver of all solar activity. Without a magnetic field, there would be no flares, no particle events, no CMEs, and probably not even a corona. Knowledge of the Sun's magnetic field is therefore of paramount importance for our understanding of energetic and eruptive events, and the only path to reliable predictive capabilities – the “holy grail” of space weather research – will be through measurements and understanding of the magnetic field topology throughout the Sun's atmosphere, from the photosphere through the chromosphere to the base of the corona (e.g. Mackay and Yeates 2012). Unfortunately, magnetic field measurements in the chromosphere and corona are very difficult, and it may be many years until we can expect to be in a position to measure and interpret them reliably and on a routine basis. Most magnetic field measurements are therefore done in the photosphere and then extrapolated into the higher layers (e.g. Wiegelmann and Sakurai 2012), despite the considerable difficulties of transforming the forced photospheric magnetograms into adequate

approximations of nearly force-free fields at the base of the corona. Since MDI provided only longitudinal magnetograms, extrapolations are limited to linear force free field models. The Helioseismic and Magnetic Imager (HMI) on SDO, which superseded SOHO/MDI with several major improvements (significantly improved spatial resolution and image cadence) offers full Stokes vector magnetic field measurement capabilities and thus the application of non-linear force free field models.

While the primary objective of SOHO/MDI was to obtain spatially resolved velocity time series of the solar atmosphere for the helioseismic study of the Sun's interior, as a by-product MDI also generated longitudinal (line-of-sight) magnetograms in the photospheric Ni I 6768 Å line, formed at a height of about 100 km above $\tau_{5000}=1$. MDI provided both full disk magnetograms with a spatial resolution of 4 arcsec as well as higher resolution (1.25 arcsec) magnetograms. The latter were limited to the MDI "high-res" field of view, a square of about 11 arcmin x 11 arcmin centered about 160 arcsec north of the equator. They were taken during special campaigns, when SOHO high rate telemetry was available. The temporal resolution of some of the MDI magnetic field data products obtained during special campaigns is as short as 1 minute. In addition to higher time resolution campaign data, MDI provided synoptic full disk magnetograms at a regular cadence of 96 minutes (15 per day) throughout the mission. While there are magnetograms available with much higher spatial resolution (e.g., from the Stokes Polarimeter on Hinode, but also from ground), the unmatched consistency, availability, and coverage of the MDI 96-min full disk magnetogram series has proven to be invaluable in nearly all research areas of solar physics, in particular also in space weather research. MDI synoptic magnetograms have been used in countless investigations aimed at reconstructing the magnetic field topology of active regions and eruptive events (e.g. Schrijver 2009). They form the basis of a large database of global potential field source surface (PFSS) models, which are frequently used as input for large-scale MHD models of the corona and heliosphere.

Far side imaging of active regions by MDI and SWAN

Solar active regions are the centers of energetic phenomena that produce flares and coronal mass ejections, whose resulting electromagnetic and particle radiation interfere with telecommunications and power transmission on Earth and pose significant hazards to astronauts and spacecraft. Imaging of far-side solar activity allows anticipation of the appearance of large active regions more than a week ahead of their arrival on the East limb of the Sun, greatly improving mid-range space weather forecasting capabilities from 1-3 days to 1-2 weeks. To use an analogy from terrestrial storm forecasting, far side images of solar active regions would offer the space weather forecaster a similar lead time to potentially hazardous events as geosynchronous satellite data of a strong tropical depression or hurricane cell far out in the Atlantic.

Just a little over 4 years after the launch of SOHO, in March 2000, scientists published an astonishing result: the first successful holographic reconstruction of features on the far side of the Sun. An active region on the far side reveals itself because its strong magnetic fields speed up the global sound waves. Because these waves travel from the near side of the Sun to the far side and back, they interfere with their multiple reflections. The result is a standing wave with a sharply defined frequency, called a *p*-mode ("p" for pressure), similar to the harmonics that resonate in an organ pipe. An active region can be compared to a small dent in the organ pipe, slightly reducing its internal volume and thereby slightly raising its resonant frequency. Soon after the initial publication of this result, the astonishing became routine, and MDI (and later

also GONG and SDO/HMI) offered daily far-side images online.

MDI was not the first SOHO instrument that provided information about activity on the Sun's far side. Half a year before the MDI release, in June 1999, the SWAN team announced a new technique to map solar activity on the Sun's far side. SWAN, short for Solar Wind Anisotropies, is used to map the whole sky in ultraviolet light. It sees a huge cloud of interstellar hydrogen that bathes the entire Solar System and interacts with the solar wind. The cloud is relatively tenuous – about 0.1 atoms per cc – yet it is thick enough to shine when illuminated by the Sun's ultraviolet light ($\text{Ly } \alpha$). This kind of observation is impossible from Earth because the atmosphere completely filters the short-wavelength ultraviolet light. Even spacecraft in orbit around the Earth are blinded to the hydrogen haze of the Solar System by a large swarm of hydrogen atoms that surrounds our planet (geocorona). SWAN full sky maps reveal “hot-spots” when the hydrogen cloud beyond the Sun glows more strongly than would be expected if the Sun were uniformly bright on its far side. The strong ultraviolet emissions from active regions on the far side of the Sun behave like beams from a lighthouse on the landscape (Fig. 4). They move in the sky in accordance with the Sun's rotation, which takes about 28 days. This allows monitoring activity on the far side of the Sun without looking at it directly and is currently used by space weather researchers in France, in combination with MDI/GONG/HMI far side helioseismology results to recreate the solar activity pattern at any time and any point on the Sun.

Fig. 4: SWAN full sky maps from 20 July 1996 (top) and ten days later (30 July 1996; bottom). The left circles show the sky brightness in $\text{Ly } \alpha$ on the far side of the Sun, the right circles the same for the sky behind the spacecraft (i.e., behind Earth). Note the distinct bright patch in the upper left image, resulting from an active region on the far side of the Sun. Ten days later, when the Sun's rotation has moved that active region to the visible face of the Sun (see lower right green EIT image), the sky behind the spacecraft is now illuminated (lower right blue image).

With the two STEREO spacecraft (in combination with SOHO and SDO) providing full 360° coverage of the Sun, the far side imaging techniques have been validated and hence are less frequently used for space weather predictions now than before the availability of STEREO data. However, in a few years, when the two STEREO spacecraft won't be able to provide full 360° coverage anymore, these techniques will become very important and valuable again.

The SWAN full-sky images are also used to predict the UV flux received by the Earth two weeks in advance and to compute the UV flux emitted toward any planet or object in the solar system. These values are produced on a regular basis and distributed through the SWAN web page. One application of this data set is the prediction of Earth's thermospheric temperature, which is the main parameter used to compute the drag effect on satellites on low earth orbit.

Multiple SOHO observations were then successfully used in October 2003 when some of the biggest active regions containing some of the largest sunspots of Cycle 23 appeared coming at the East limb of the Sun (Fig. 3 and 5) - already spreading X-rays, extreme ultraviolet radiation, high energy particles, and coronal mass ejections into interplanetary space. At that time space weather predictors had an earlier warning since the regions were seen on the far side of the Sun with seismic holography and other techniques developed with SOHO. The significance of that two-week outburst of solar activity has been documented in a NOAA Service Assessment (http://www.swpc.noaa.gov/Services/SWstorms_assessment.pdf). Not

only were the MDI far-side techniques presaging intense activity on the Sun's backside, but two other SOHO instruments also provided "early warning" that there was unusual activity on the Sun's far-side: the LASCO observers noted extremely fast CMEs without associated activity counterparts on the Earth-facing hemisphere of the Sun; and SWAN noted unusual EUV intensity coming from the Sun's far-side.

Fig. 5: A sequence of LASCO C3 images following the event depicted in Fig. 3 ("Halloween Storms" of 28 October 2003). In the upper left image (11:18) the halo CME is still behind the occulting disk. Planet Mercury is the bright feature at about 10 o'clock near the edge of the occulting disk; numerous bright coronal streamers can be seen extending out to the edge of the field of view; the dark linear feature at 7 o'clock is the shadow of the pylon holding the occulting disk; numerous stars are seen in the background. Upper right: The halo CME has emerged from behind the C3 occulting disk at 11:42. The remaining images are a time sequence showing the progression of the halo CME and the onset of one of the most intense energetic solar proton events in SOHO's lifetime. The energetic protons are racing ahead of the CME plasma at nearly the speed of light and an hour after the eruption start bombarding the CCD detector. After about 12 hours, the images are practically useless because of the intensity of the proton storm.

Predicting solar proton events

Sudden increases in the fluence of >30 MeV protons in SEP events pose a hazard to human space activities and robotic space missions (cf. Fig. 5). A new method, based on SOHO/COSTEP measurements of relativistic (150 keV - 10 MeV) electrons, permits up to an hour of warning for the later arriving protons in SEP events (Posner, 2007). The electrons act as test particles by probing the continuously changing heliospheric transport conditions in the same region of the heliosphere through which the slower-moving protons have to propagate. The new method was for the first time tested under operational conditions during the February 2008 Space Shuttle Atlantis mission, which transported ESA's Columbus laboratory to the International Space Station. NASA-Goddard's Space Weather Research Center has included this method in its array of research-grade forecasting tools that routinely provide information to the human and robotic exploration fleet.

CELIAS proton monitor measurements of the solar wind and ICMEs

In addition to interplanetary shock fronts associated with CMEs, co-rotating interaction regions (CIRs) and their associated high-speed wind streams can drive geomagnetic activity. Upstream measurements of the solar wind plasma are therefore important for the short-term (30-60 min) prediction of the onset of geomagnetic activity. The CELIAS/MTOF proton monitor provides measurements of bulk speed, density, thermal speed and north/south flow direction in near-real time during DSN contact times. The only other available real-time data set is from ACE, which is seriously degraded during intense energetic particle events, and from the STEREO spacecraft, which are now on the far-side of the Sun. Unfortunately, there is no magnetometer onboard SOHO (it was de-scoped very early during SOHO's development), and hence no measurements of the solar wind plasma's magnetic field. This is arguably the biggest shortcoming of SOHO's *in situ* solar wind measurements and explains why ACE solar wind data are more widely used by the space weather community.

Conclusion

SOHO is a robust solar observatory that has revolutionized both the curiosity-driven science of solar physics and the application of heliophysics that is now known as space weather. During the first year of SOHO's operation it became clear that the significant improvements in image quality, combined with near-real-time return of LASCO and EIT images (almost 20 hours per day) would define the "gold standard" for mid-range (1-3 day) space weather forecasting. Researchers and forecasters have relied on LASCO and EIT data in various techniques, and combined with different auxiliary observations, to predict the arrival time of CMEs and interplanetary shocks at Earth.

Cross-References

SDO
STEREO
ACE

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