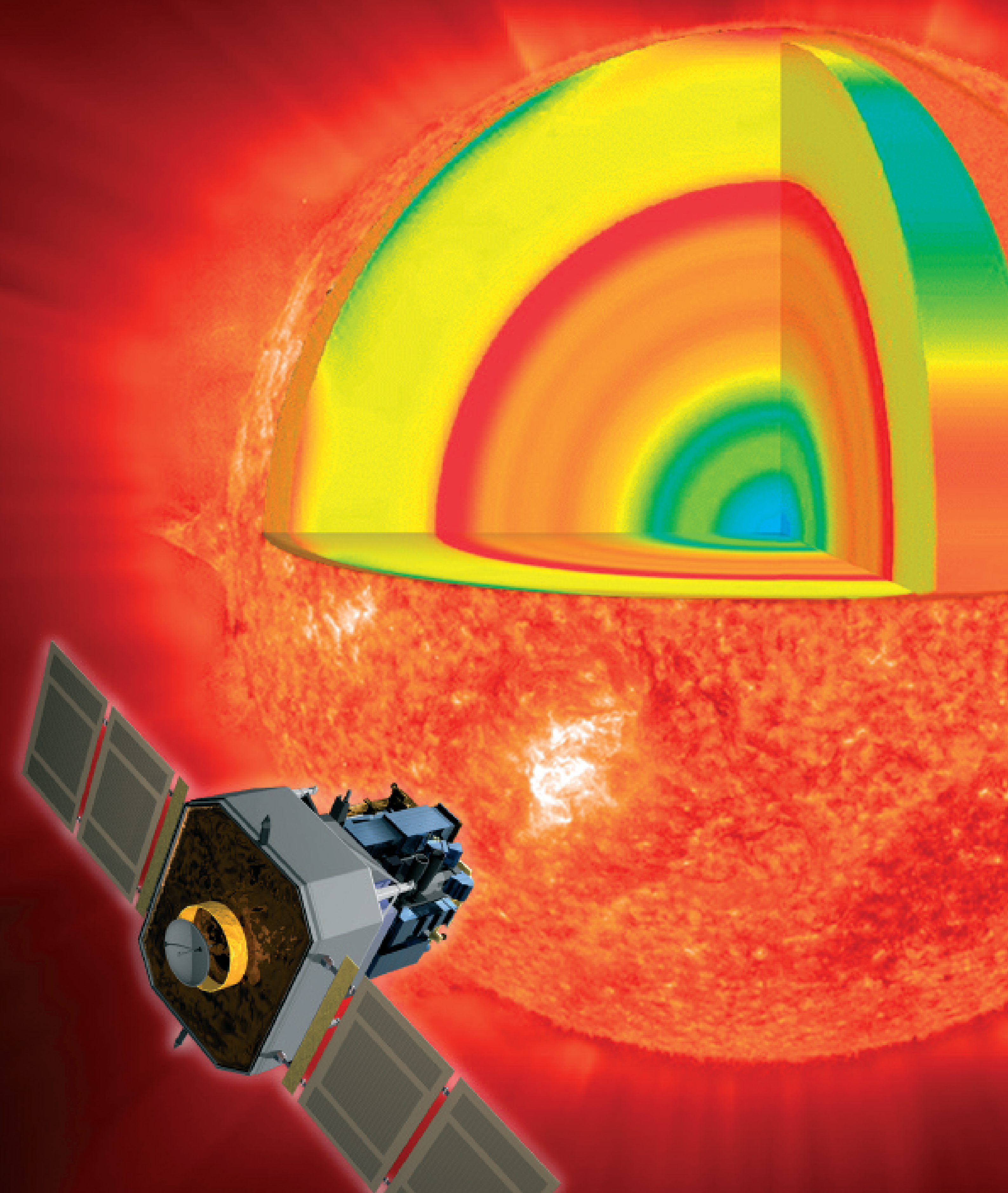
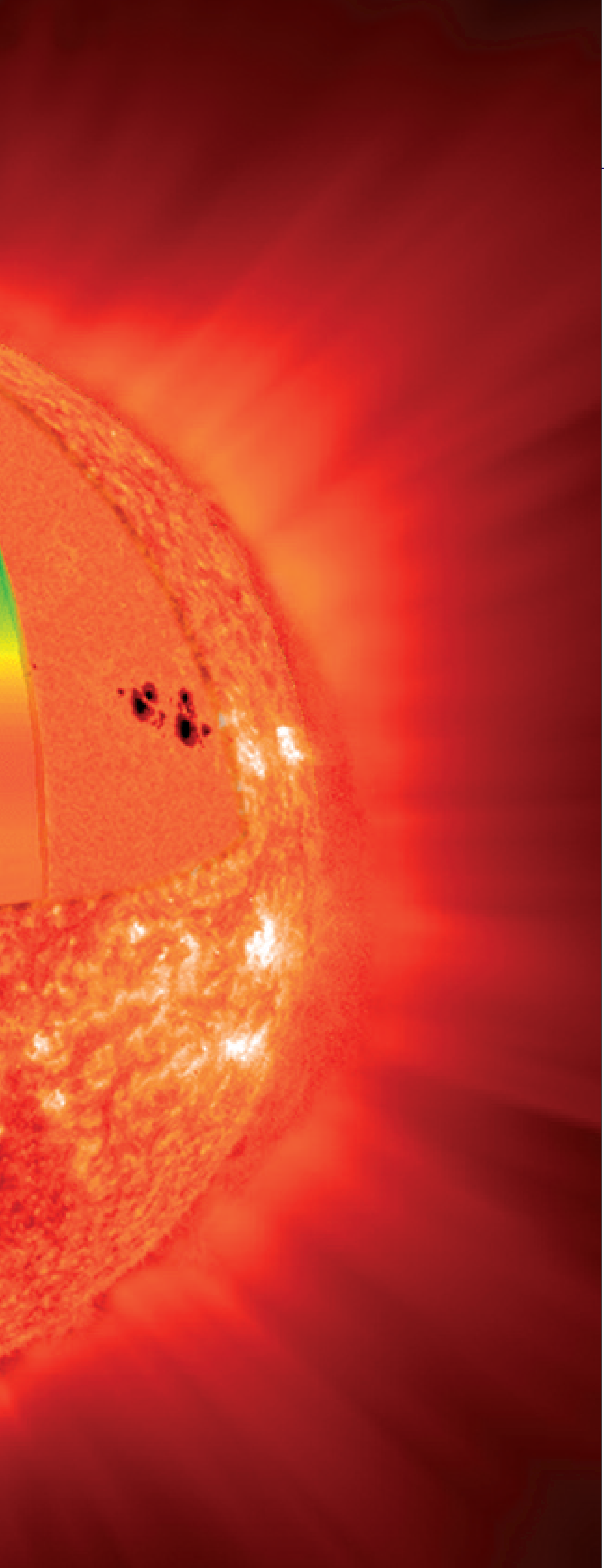
10 Years of SOHO





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Since its launch on 2 December 1995, SOHO has revolutionised our understanding of the Sun. It has provided the first images of structures and flows below the Sun's surface and of activity on the far side. SOHO has revealed the Sun's extremely dynamic atmosphere, provided evidence for the transfer of magnetic energy from the surface to the outer solar atmosphere, the corona, through a 'magnetic carpet', and identified the source regions of the fast solar wind. It has revolutionised our understanding of solar-terrestrial relations and dramatically improved our space weather-forecasting by its continuous stream of images covering the atmosphere, extended corona and far side. The findings are documented in an impressive number of scientific publications: over 2500 papers in refereed journals since launch, representing the work of over 2300 individual scientists. At the same time, SOHO's easily accessible, spectacular data and fundamental scientific results have captured the imagination of the space science community and the general public alike. As a byproduct of the efforts to provide real-time data to the public, amateurs now dominate SOHO's discovery of over 1100 Sun-grazing comets.

Introduction

We all live in the extended atmosphere of a magnetically active star. While sunlight sustains life, the Sun's variability produces streams of high-energy particles and radiation that can affect life. Understanding the changing Sun and its effects on the Solar System has become one of the main goals of the SOHO mission, which was launched to address three fundamental science questions: what is the structure and dynamics of the solar interior, how is the corona heated, and how is the solar wind accelerated?

A consortium of European space companies led by prime contractor Matra Marconi Space (now EADS Astrium) built SOHO under overall management by ESA, and international consortia developed its suite of 12 instruments. NASA launched SOHO on 2 December 1995, inserting it into a halo orbit around the L1 Lagrangian point in February 1996.

The SOHO Experiment Operations Facility (EOF), at NASA's Goddard Space Flight Center, serves as the focal point for mission science planning and instrument operations. Half of the 12 SOHO Principal Investigator Teams have resident representatives at the EOF, where they receive telemetry and send commands directly from their workstations through the ground system to their instruments.

An overview article cannot do justice to the 2500-plus articles published in the refereed literature and an even greater number in conference proceedings and other publications. Here, we touch upon a few selected results. Highlights from the first 4 years of SOHO were described in *Bulletin* 102 (May 2000).

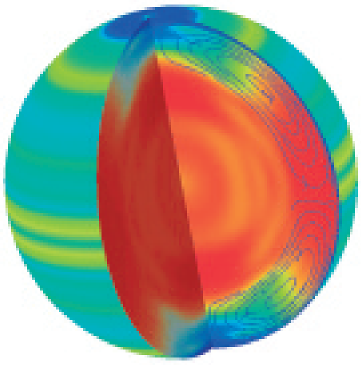
Making the Sun Transparent

Just as seismology reveals the Earth's interior by studying earthquake waves, solar physicists probe the Sun's interior via 'helioseismology'. The oscillations detectable at the visible surface are due to sound waves reverberating through the Sun's inner layers. By precisely measuring the frequencies, we can infer the Sun's temperature, density, atomic abundances, interior structure and the age of the Solar System, and even pursue such esoteric matters as testing the constancy of the gravitational constant.

One of the most productive instruments, the Michelson Doppler Imager (MDI), shows oscillations of the whole Sun. It has revealed strong variations in the velocity of the plasma in the solar interior, and found an 'adjustment' layer at the base of the convection zone. This layer, about 220 000 km beneath the visible surface (about a third of the way down to the Sun's centre), connects the more orderly interior of the Sun (the radiative zone) with the more turbulent outer region (the convection zone). It is of particular interest because this is where the solar dynamo that creates the Sun's magnetic field is believed to operate. In this region, the speed of the gas changes abruptly. Near the equator, the outer layers rotate faster than the inner layers. At mid-latitudes and near the poles, the situation is reversed.

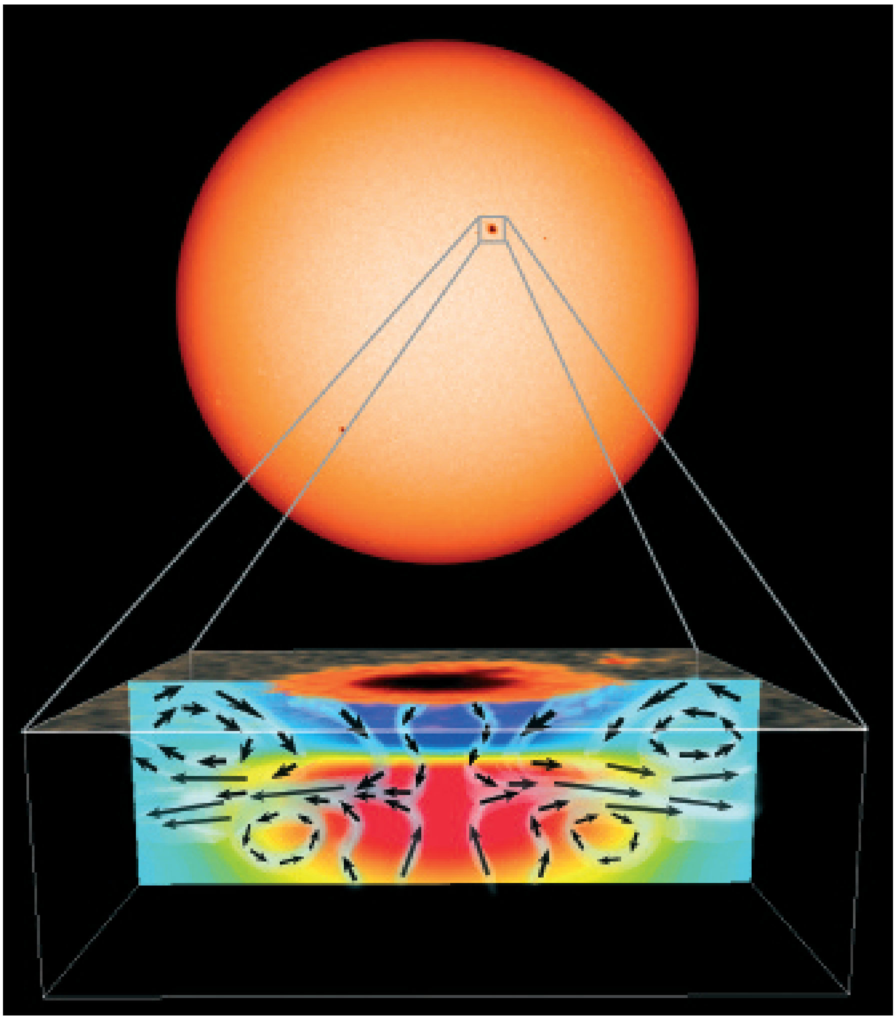
MDI data have revealed a fascinating picture of the large-scale, subsurface dynamics of the Sun, with dramatic changes with the solar cycle. We all know of the crucial importance of large-scale streams in our atmosphere (e.g. jet stream) and in the oceans (e.g. gulf stream) for Earth's climate. MDI has for the first time enabled us to observe such large-scale streams inside the Sun. Researchers discovered transient storms, high- and low-pressure zones, and swirling wind flows near active regions that vary from day to day like weather patterns on Earth's surface.

Ever since MDI began to deliver helioseismic information at finer spatial scales than previously available, the new field of 'local-area helioseismology' has developed rapidly. New methods allowed construction of the first true 3-D images and flow maps of the interior of a star, and even the first images of the far side of our Sun. Applying the novel 'acoustic tomography' method to MDI data, scientists could for the first time study the structure of sunspots below the Sun's surface. They were thus able to solve two long-standing puzzles about these blemishes on the Sun, which have been a source of wonder ever since they were described (and drawn in painstaking detail) by Galileo Galilei: how deep do the spots extend below the surface, and how can sunspots last for several weeks without breaking up? The MDI team found the answers: strong, converging downflows stabilise the structure of the sunspots, and sunspots are relatively shallow.



Solar rotation and polar flows of the Sun deduced from MDI measurements. The left side shows the difference in rotation speed between various areas. Red-yellow is faster than average, while blue is slower than average. The light orange bands are zones that move slightly faster than their surroundings. The cutaway reveals rotation speed inside the Sun. The large dark red band beneath the solar equator is a massive fast flow of hot, electrically-charged gas: plasma. The blue lines at right show the surface flow from the equator to the poles. The return flow indicated at the bottom of the convection zone has not yet been observed

'Solar Subsurface Weather' map, showing magnetic field (black/red) and average 'wind' flow (blue arrows) under the solar surface



Using advanced analysis techniques, SOHO/MDI can reveal the temperature and flow structure beneath sunspots

Just a little over 4 years after the launch of SOHO, 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 sound waves. The difference becomes evident when sound waves shuttling back and forth fall out of step with one another. In the meantime, the astonishing has become routine, and MDI offers daily far-side images online, at *http://soi.stanford.edu/data/full_farside/*.

Violent solar activity occasionally disrupts satellites, radio communications and power systems. Advance warning of magnetic storms brewing on the far side that could rotate with the Sun and threaten Earth is therefore of vital importance for space weather forecasting.

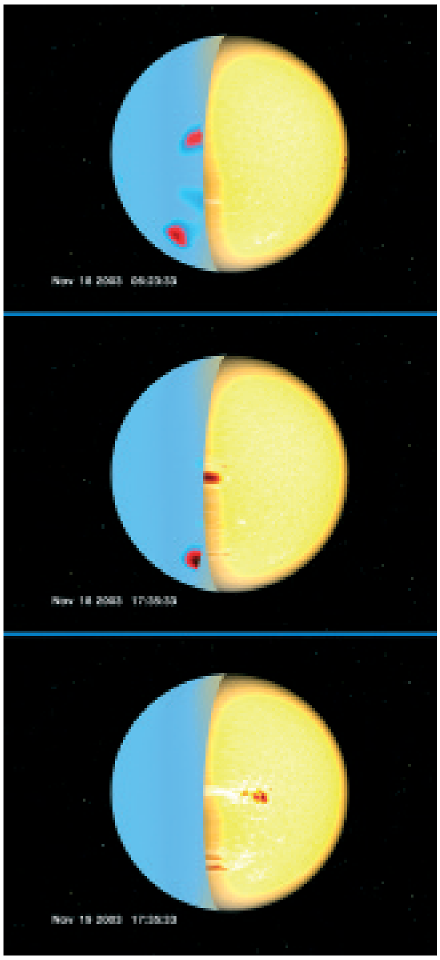
The Sun's Dynamic Corona

The outer atmosphere of the Sun, the corona, has a typical temperature of about 1 million K and emits light mainly in the ultraviolet (UV) part of the spectrum. It is this radiation from the Sun's hot corona that controls the composition and dynamics of Earth's upper atmosphere. Water vapour and ozone are especially sensitive to changes in the Sun's UV output. Fortunately, Earth's atmosphere protects us from this harmful radiation. This also means that we have to leave Earth's atmosphere behind and observe the Sun from space.

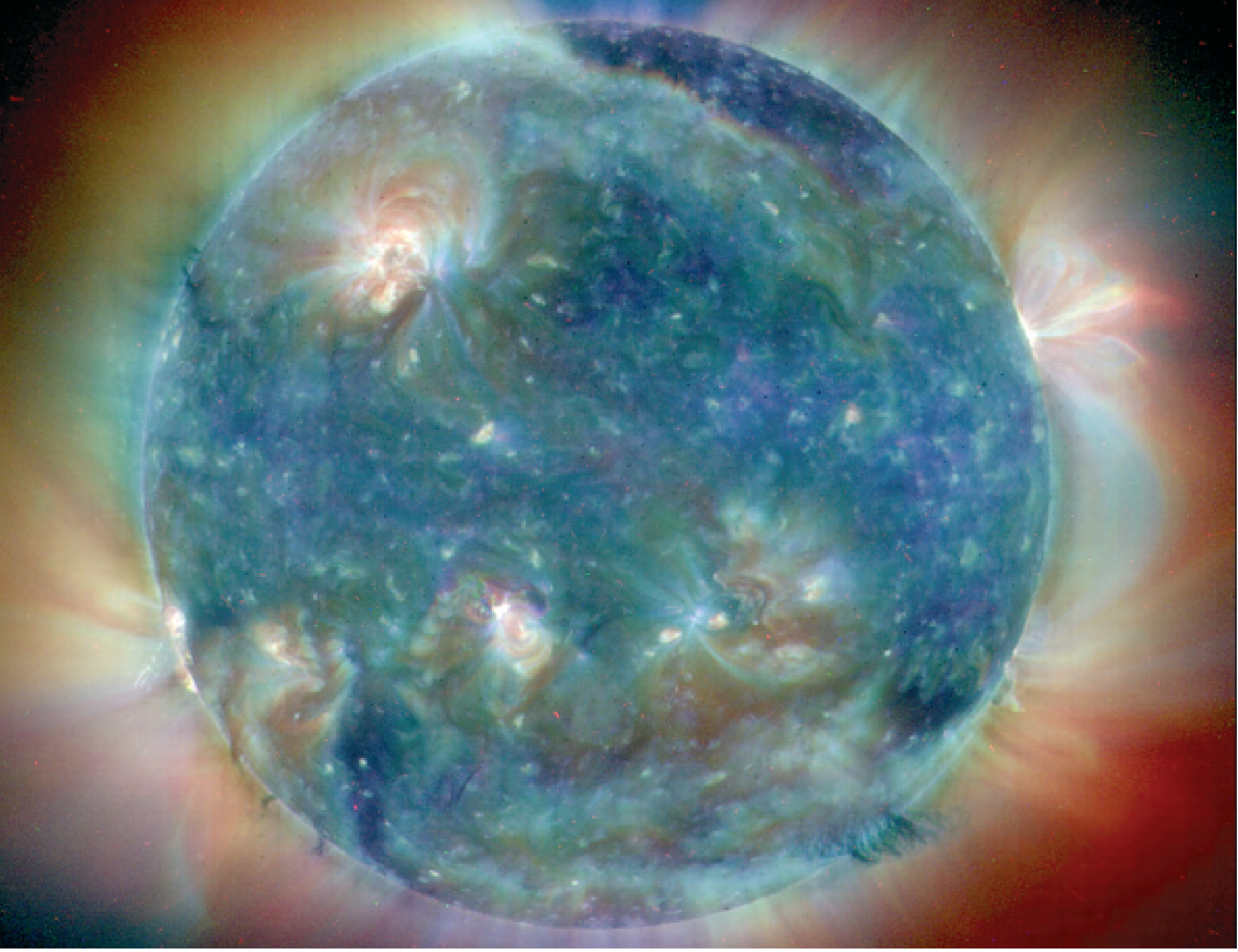
SOHO's Extreme ultraviolet Imaging Telescope (EIT) provides us with stunning images of the Sun's corona, showing delicate coronal loops, bright flares and intriguing coronal holes. EIT and the UV spectrometers SUMER and CDS show us that the outer solar atmosphere is extremely dynamic and changing, and that plasma flows play an extremely important role.

Gone With the Solar Wind

The solar wind is a stream of mainly electrons and protons flowing from the



Holographically reconstructed side view of the Sun showing the two large active regions 10486 and 10488 as they rotate from the far side (left) to the hemisphere visible from Earth (right). During the previous rotation, these two active regions were the source of the powerful 'Halloween' storms in 2003, which included the largest ever recorded X-ray flare

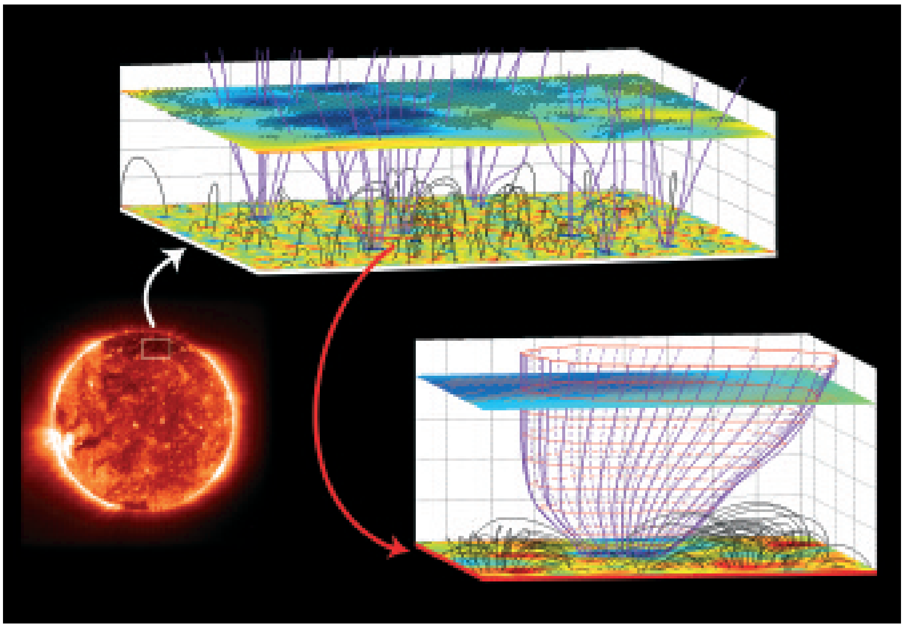


Composite image of the solar corona with three wavelengths (171 Å as blue, 195 Å as yellow and 284 Å as red) combined to show features unique to each wavelength. The 171 Å filter captures emission at about 1 million K, 195 Å at about 1.5 million K, and 284 Å at about 2.5 million K

Sun faster than 3 million km/h. It is essentially the hot solar corona expanding into interplanetary and interstellar space. It deforms Earth's magnetosphere and ionises atoms in our upper atmosphere, causing beautiful aurorae.

Interpreting data from the Ultraviolet Coronagraph Spectrometer (UVCS), scientists found evidence that the solar wind streams out of the Sun by 'surfing' on waves produced by vibrating magnetic field lines, just like an ocean wave carrying a surfer.

Using SUMER, scientists have mapped the outflow of plasma from coronal holes, and found a clear connection between the flow speed and the network structure of the chromosphere, a lower layer of the atmosphere. This is the first spectroscopic discovery of the source of the fast solar wind. In a later study, a Chinese-German team has used SUMER and MDI data to show that the solar wind

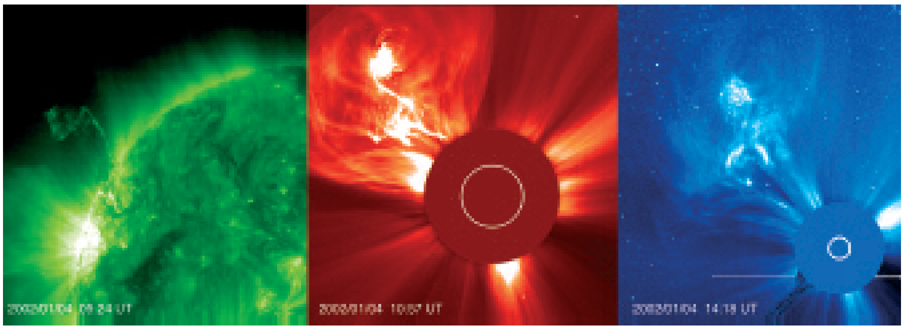


The solar wind emerges from coronal funnels. The magenta curves are open magnetic field lines, dark grey arches show closed ones. The lower plane shows the magnetic vertical component measured by MDI (blue to red). The upper plane shows Ne VIII Doppler shifts from SUMER (hatched regions have large outflows), together with the inclination of the magnetic field (blue to red), as extrapolated from the MDI measurements escapes from the Sun in funnels of open magnetic fields.

SOHO, the Space Weather Watchdog

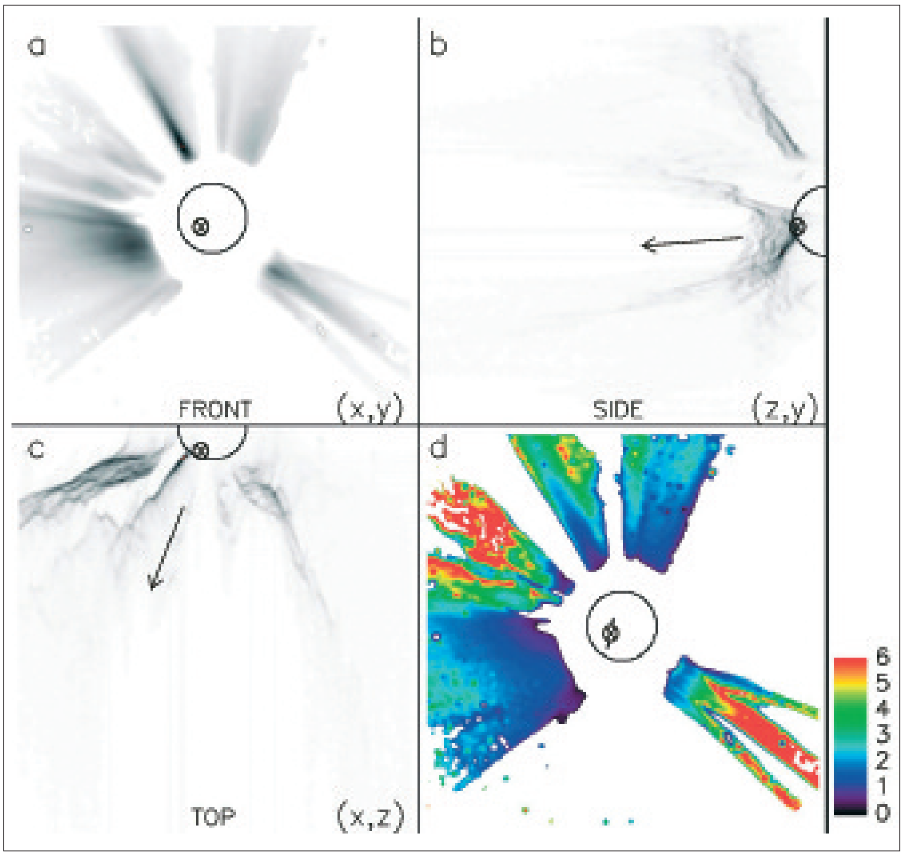
While the Sun's total radiative output is reassuringly constant, it is at the same time a dynamic and violent star. Besides emitting a continuous stream of plasma in the solar wind, the Sun periodically releases huge amounts of matter in coronal mass ejections (CMEs). These are the most powerful eruptions in the Solar System, with billions of tonnes of electrified gas propelled from the Sun's atmosphere into space at millions of km/h. If they hit Earth, these immense clouds can cause large magnetic storms in our magnetosphere and upper atmosphere. Researchers believe they are launched when solar magnetic fields become strained and suddenly snap into a new arrangement, like a rubber band twisted to breaking point.

Apart from causing beautiful aurorae, CME disturbances can damage satellites, disrupt telecommunications, endanger astronauts, lead to corrosion in oil pipe lines and cause current surges in power lines. As our society becomes increasingly dependent on space-based technologies, our vulnerability to 'space weather' becomes more obvious, and the need to understand it and mitigate its effects becomes more urgent. In recent years, forecasting the conditions in the near-Earth environment and the 'geo-effectiveness' of CMEs and solar flares has become one of the key research areas in solar and solar-terrestrial physics; SOHO is playing a pioneering role in this new discipline. While satellites that make *in situ* measurements in near-Earth orbits can give only about a 2-hour alert of solar storms, SOHO's coronagraphs and EUV imager observe the source of CMEs and flares and thus provide up to 3 days' warning, sufficient to save costly equipment. SOHO's LASCO and EIT are the primary source of operational information on the location, speed and orientation of CMEs from the Earth-facing hemisphere of the Sun. These remote-sensing observations are complemented by the CELIAS, COSTEP and ERNE *in situ* measurements of the arrival of the CME and energetic particles at the L1 Lagrangian point.

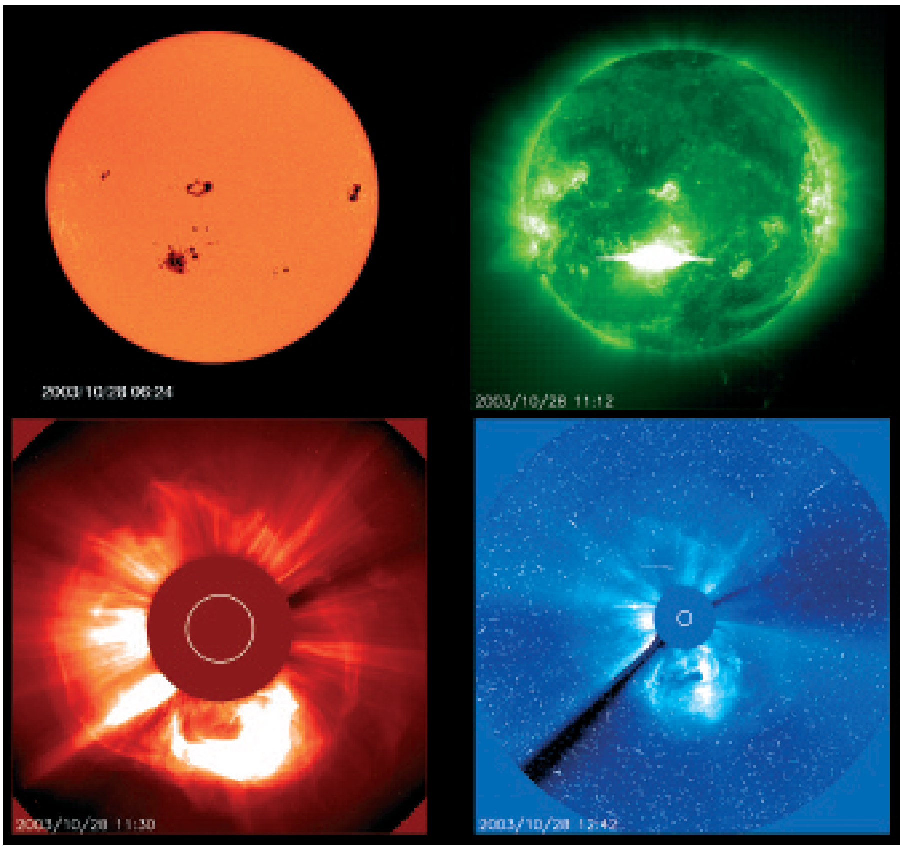


This fiery coronal mass ejection shows stunning details in the ejected material, revealed by SOHO's LASCO coronagraph. The direct sunlight is blocked (red disc), exposing the surrounding faint corona. The white circle represents the approximate size of the Sun

The LASCO team has compiled an extensive catalogue that summarises the mass, speed, acceleration, angular width, position and so on of the more than 10 000 CMEs observed since launch. This catalogue has been used in numerous studies, including how the number of CMEs varies with the solar cycle: the rate increases from 0.5 per day during solar minimum to over 6 per day during solar maximum. Using LASCO data, scientist can also for the first time reconstruct 3-D images of CME structures. Combined



A coronal mass ejection heading almost directly towards Earth, observed by LASCO C2. The size of the Sun is indicated by a circle, and the x-marked circle on the Sun shows the origin of the CME. Panel (a) shows the total intensity (darker means more intense) as imaged directly by LASCO. Panel (d) is a topographic map of the material shown in panel (a). The distance from the plane of the Sun to the material is colour-coded; the scale in units of solar radii is shown on the side. Panels (b) and (c) show the intensity as it would appear to an observer positioned to the side of the Sun or directly above it, respectively



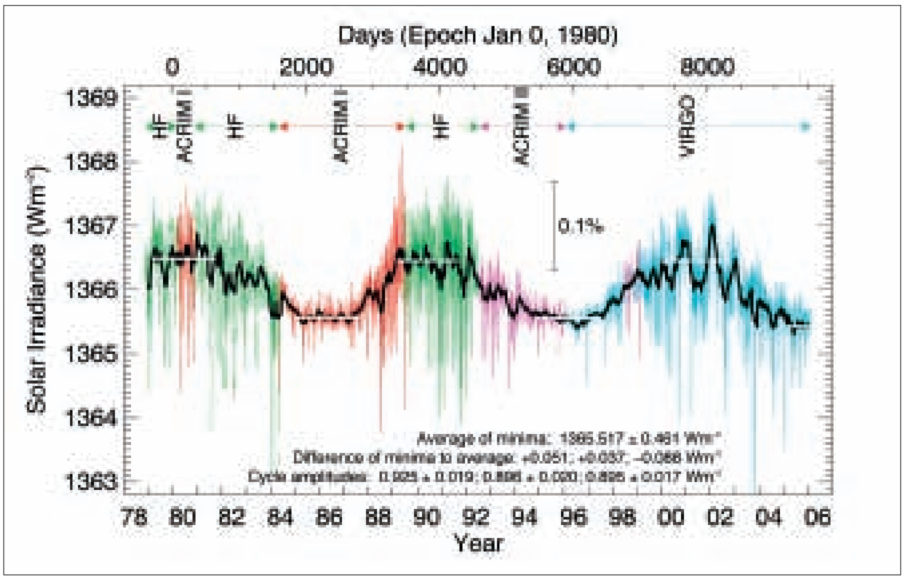
Active Region 10486 unleashed a spectacular show on 28 October 2003: an X 17.2 flare, a fast-moving coronal mass ejection and a strong solar energetic particle event. From top left: giant sunspot groups seen by MDI in white light; the flare as seen by EIT at 195 Å; the fast-moving CME in the LASCO C2 coronagraph, then in the LASCO C3 coronagraph, with the particle shower becoming visible as 'snow' in the image. The cloud struck Earth's magnetosphere only19 hours later, almost a record speed

with other views from the coronagraphs on the STEREO satellite to be launched later this year, this technique should significantly reduce ambiguities in the reconstruction of interplanetary CME morphology.

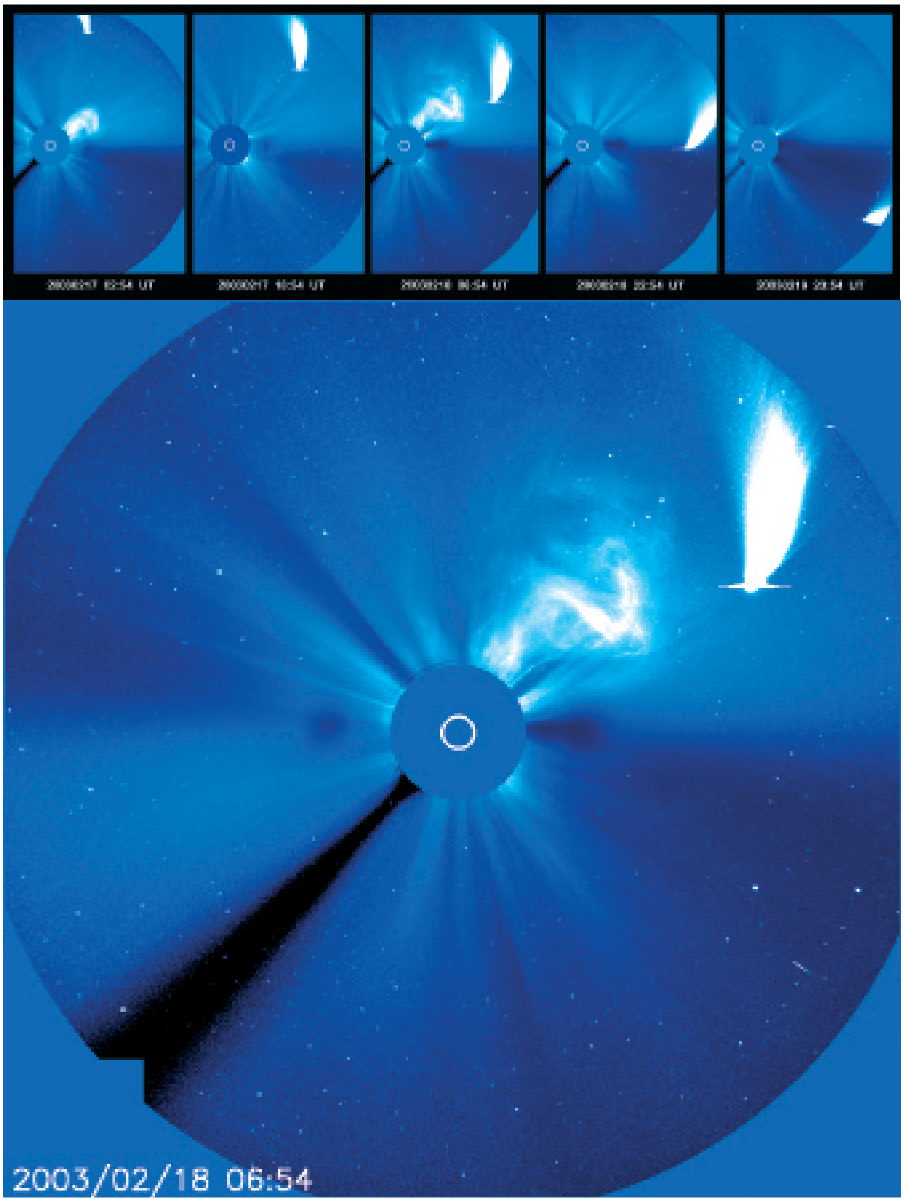
During 2 weeks in October/November 2003, the Sun featured three unusually large sunspot groups, which gave rise to 11 X-class flares (including the strongest ever recorded), numerous CMEs and two large proton storms. Satellites, power grids, radio communications and navigation systems were significantly affected. The events, among the best-observed ever, will be analysed for years to come. The events triggerred unprecedented attention from the media and public. SOHO images appeared in nearly every major news outlet. Furthermore, the great public interest wiped out all existing SOHO web traffic records, with the web server serving over 31 million page requests and 4.3 Terabyte of data in just one month.

Measuring the Total Solar Irradiance

A crucial question is whether the Sun's total irradiance is changing on longer time scales. Indications of such a change would have a broad social and political impact as governments would have to devise strategies in response to global warming. SOHO's VIRGO instrument is monitoring the total solar irradiance (TSI), also known as the 'solar constant'. The VIRGO team has constructed composites of TSI measurements from SOHO and other spacecraft over the last 26 years. From this composite record, it now appears that there is no evidence for a significant long-term trend in the TSI: the total radiation from the Sun does not show any systematic brightness increase or decrease on observed time scales. However, while the total solar irradiance varies by less than 0.1% over the 11-year solar cycle, the irradiance in the extreme-UV (EUV) part of the spectrum changes by as much as 30% within weeks and by a factor of



The composite total solar irradiance (TSI) over two solar cycles, combining data from multiple spacecraft instruments, does not show a long-term change. Different colours indicate different data sources; the blue data are from SOHO's VIRGO



Perihelion passage of comet NEAT (C/2002 V1) in February 2003, as imaged by LASCO C3

2–100 (depending on wavelength) over the solar cycle. Detailed knowledge of the solar spectral irradiance is crucial for understanding climate variability, and to disentangle natural variations from anthropogenic climate changes.

SOHO, the Comet Finder

SOHO is providing new measurements not only about the Sun. On 5 August 2005, Toni Scarmato, a high school teacher from Calabria, Italy, discovered SOHO's 999th and 1000th comets. As of February 2006, LASCO had detected over 1100 comets, most of them 'Sun-grazers'. These comets pass very close to the Sun and grow prominent tails as their icy cores are heated. Nearly half of all comets for which orbital elements have been determined (since 1761) were discovered by SOHO, and over two-thirds of those by amateurs accessing LASCO data via the Web. This is a field where amateurs can actively contribute to scientific research; each day, numerous people from all over the world download the near-realtime data to search for new comets.

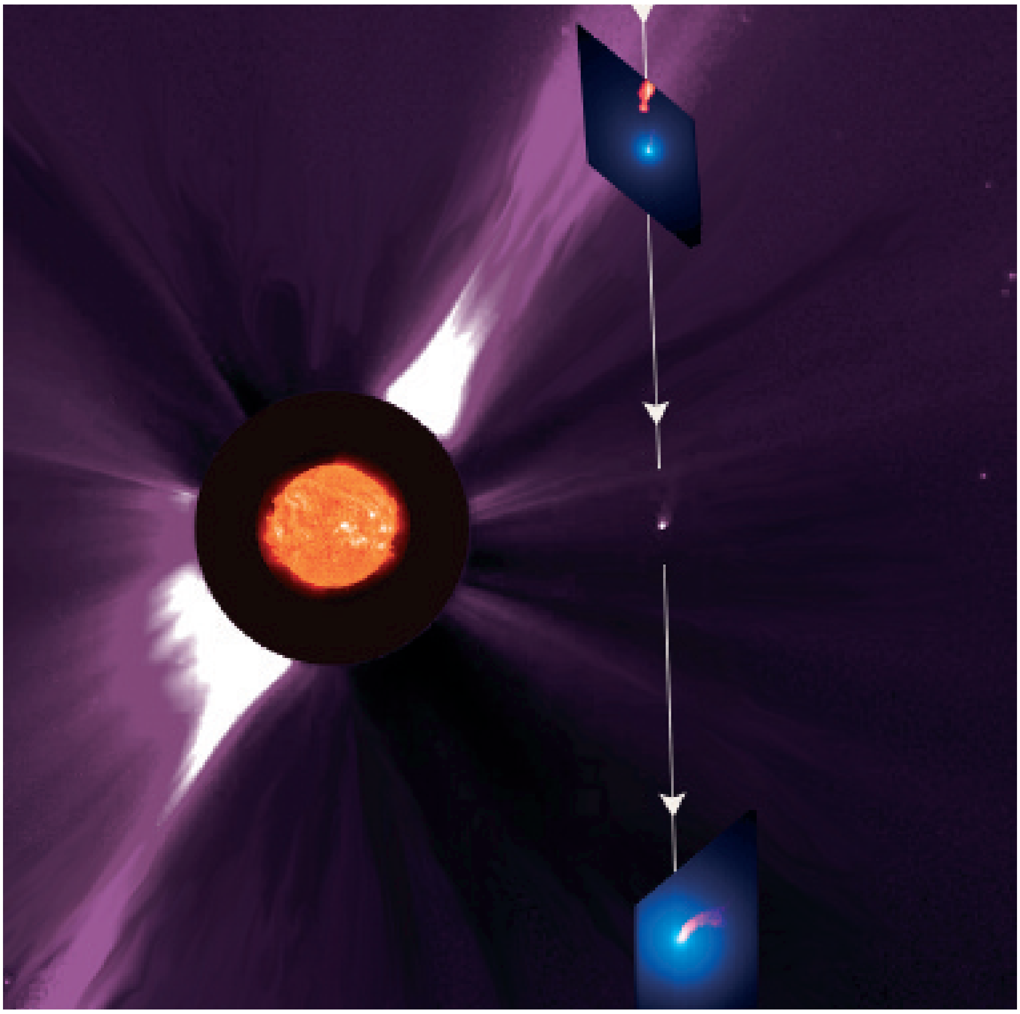
As the brightest, most spectacular comet ever observed by SOHO, comet NEAT (C/2002 V1) provided some enticing data for further study, thanks to a grazing encounter with a coronal mass ejection. The LASCO C3 observations during 16–20 February 2003 suggest interaction between the comet's ion tail and other magnetic fields in the outer corona at the time of the oblique impact with the CME. This is the first time that such an event has been imaged, and no comet has ever been observed closer to the Sun.

The analysis of high-resolution spectroscopic observations of comet C/2002 X5 (Kudo-Fujikawa) from UVCS has revealed a near-spherical cloud of neutral hydrogen and a variable tail of ionised carbon (C^+ and C_2^+) that disconnected from the comet and was subsequently regenerated.

SOHO's SWAN instrument monitored the break-up of comet LINEAR C/1999 S4. The total amount of water vapour observed by SWAN from 25 May to 12 August 2000 was estimated at 3.3 million tonnes. Only about 1% of this was left on 6 August, when observations by the Hubble Space Telescope of the dying comet's fragments gave an estimate of the total volume. Combining the numbers gives a remarkably low value for the density: about 15 kg/m^3, compared with 917 kg/m^3 for familiar non-porous ice. Even allowing for an equal amount of dust grains, 30 kg/m^3 is far less than the 500 kg/m^3 often assumed by comet scientists.

Conclusions and SOHO's Future

The journey has not always been easy. For example, an unexpected loss of contact occurred on 25 June 1998. Fortunately, the mission was completely recovered in one of the most dramatic rescue efforts in space, and normal operations could be resumed in mid-November 1998 after the successful recommissioning of the spacecraft and all 12 instruments. Despite the subsequent failures of all three gyroscopes (the last in December 1998), new gyroless control software installed by February 1999 allowed SOHO to return to normal scientific operations, providing an



Composite image of comet C/2002 X5 (Kudo-Fujikawa) as it passed within 0.2 AU of the Sun in late January 2003. The path of the comet is in white, with arrows indicating the direction of travel. The solar disc is shown as an EIT 304 Å image. The background is a combination of LASCO C2 and C3 images of the corona in visible light, and the blank ring represents the occulting disc of the C2 camera. LASCO also reveals the comet in the optical, as the fuzzy white dot to the right of the Sun. The zoomed-in images at right depict the comet in the H I Lyman-alpha 1216 Å line (blue) and the C III 977 Å line (red-orange). The C III emission has never been seen before in a comet. At upper right, the comet's main plasma tail has disconnected and is drifting anti-sunward even as a new, dim plasma tail is born from the nucleus. By the time of the second UVCS image, the new plasma tail has brightened and is beginning to turn as the comet heads away from the Sun

even greater margin of safety. This made SOHO the first 3-axis-stabilised spacecraft to operate without a gyroscope. A third crisis occurred in June 2003, when SOHO's main antenna became stuck. Using the secondary antenna and software for intermittent recording, however, even this problem was overcome, and the observations continue.

In complex areas of research such as solar physics, progress is not made by just a few people. The scientific achievements of the SOHO mission are the results of a concerted, multi-disciplinary effort by a large international community of solar scientists, involving sound investment in space hardware coupled with a vigorous and well-coordinated scientific operation and interpretation. The interplay between theory and observations has delivered many new insights and will continue to do so for many years.

In its 10 years since launch, SOHO has provided an unparalleled breadth and depth of information about the Sun, from its interior, through the hot and dynamic atmosphere, to the solar wind and its interaction with the interstellar medium. Research using SOHO observations has revolutionised our understanding of the Sun and space weather. The coming years promise to be similarly exciting and rewarding, when SOHO observations are complemented and enhanced by those from NASA's STEREO and Japan's Solar-B missions, affording new opportunities for improved understanding of the Sun-heliosphere system. After the launch of NASA's Solar Dynamics Observatory, SOHO's direct descendant, the capabilities of some SOHO instruments will be eclipsed. But not all: the LASCO coronagraph observations and VIRGO total solar irradiance measurements will continue to make crucial and unique contributions to the International Living With a Star (ILWS) programme.

Acknowledgements

The great success of the SOHO mission is a tribute to the many people – too many to name here – who designed and built this exquisite spacecraft and its excellent instruments, to the engineers who brought it back from the dead (twice), and to the many people who diligently work behind the scenes to keep it up and running.

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Further information on SOHO and its achievements can be found at http://soho.esac.esa.int/