NEARLY EIGHT YEARS OF SOHO OBSERVATIONS – SOME HIGHLIGHTS

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Abstract

Since its launch on 2 December 1995, the Solar and Heliospheric Observatory (SOHO) has provided an unparalleled breadth and depth of information about the Sun, from its interior, through the hot and dynamic atmosphere, and out to the solar wind. SOHO has continued to revolutionize our understanding of the Sun with its 24 hour per day observations of our daylight star. The main objectives of the SOHO mission was to study the structure and dynamics of the solar interior, the heating of the solar corona, and the acceleration of the solar wind. Five years later, science teams from around the world have made great strides toward answering these "big three" questions. At the same time, SOHO's easily accessible, spectacular data and basic science results have captured the imagination of the space science community and the general public alike. This presentation will summarize some of the scientific highlights and illustrate how SOHO is monitoring the energy output from the Sun and how it acts as s watchdog for solar storms. It will also summarize some of the space weather effects on the SOHO spacecraft itself.

The SOHO Spacecraft

The SOHO mission (Domingo, Fleck & Poland, 1995) is a major element of the International Solar Terrestrial Programme (ISTP), and, together with Cluster, forms the Solar Terrestrial Science Programme (STSP), the first cornerstone in ESA's long-term science programme 'Horizons 2000'. ESA was responsible for the spacecraft's procurement, integration and testing. It was built in Europe by an industry team led by Matra Marconi Space (now called Astrium). Weighing in at 1,850 kg, the SOHO spacecraft measures about 9.5 m across with its solar panels extended and is 4.3 m high. NASA provided the launcher, launch services and ground-segment system and is responsible for in-flight operations. Mission operations are conducted from NASA/Goddard Space Flight Center (GSFC).

SOHO was launched by an Atlas II-AS from Cape Canaveral on 2 December 1995 and was inserted into its halo orbit around the L1 Lagrangian point on 14 February 1996, six weeks ahead of schedule. Commissioning of the spacecraft and the scientific payload was completed by the end of March 1996. The launch was so accurate and the orbital manoeuvres were so efficient that enough fuel remains on board to maintain the halo orbit for several decades, many times the lifetime originally foreseen. An extension of the SOHO mission for a period of five years beyond its nominal mission duration (2 years), i.e. until March 2003, was approved in 1997 by ESA's

Science Programme Committee (SPC). A second extension of another four years, i.e. until March 2007, was granted by the SPC in 2002. This will allow SOHO to cover a complete 11-year solar cycle.

SOHO has a unique mode of operations, with a "live" display of data on the scientists' workstations at the SOHO Experimenters' Operations Facility (EOF) at NASA/Goddard Space Flight Center, where the scientists can command their instruments in real-time, directly from their workstations.

The Solar Interior

Just as seismology reveals the Earth's interior by studying earthquake waves, solar physicists probe inside the Sun using a technique called "helioseismology" (e.g. Christensen-Dalsgaard, 2002). The oscillations detectable at the visible surface are due to sound waves reverberating through the Sun's interior, providing information about the structure and dynamics of the regions they pass through.

Data obtained with the Michelson Doppler Imager (MDI) revealed "zonal bands" in the northern and southern hemispheres where currents flow at different speeds (~ 5 m/s) relative to each other (Schou et al., 1998, Schou, 1999). The zonal bands were found to migrate towards the equator with time, and there are indications that they penetrate down to the bottom of the convection zone (Vorontsov et al., 2002).

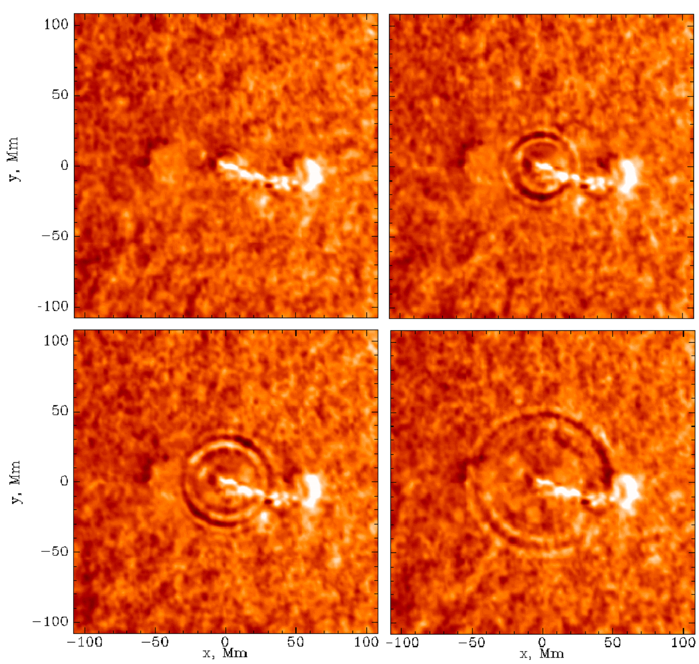

Figure 1. Seismic waves ('sun quake') produced by a solar flare on 9 July 1996. (From Kosovichev & Zharkova, 1998)

MDI has also made the first observations of seismic waves from a solar flare (Kosovichev & Zharkova, 1998), opening up possibilities of studying both flares and the solar interior. During the impulsive phase of the X2.6 class flare of 9 July 1996 a high-energy electron beam caused an explosive evaporation of chromospheric plasma at supersonic velocities. The upward motion was balanced by a downward recoil in the lower chromosphere which excited propagating waves in the solar interior. On the surface the outgoing circular flare waves resembled ripples from a pebble thrown into a pond (Figure 1). The seismic wave propagated to at least 120,000 km from the flare epicenter with an average speed of about 50 km/s on the solar surface.

Currents of gas deep inside the Sun appear to pulsate like the blood in human arteries, speeding and slackening every 16 months (Howe et al., 2000). This result comes from combined observations by MDI and GONG (Global Oscillations Network Group), a worldwide chain of ground stations. The observed variations in the flows of gas occur about 220,000 km beneath the visible surface - almost a third of the way down to the centre of the Sun. Here is the supposed dynamo region, where the turbulent outer region, the convection zone, meets the more orderly interior, the radiative zone. In this region, called the tachocline, the rotation speed of the gas changes abruptly from differential rotation to uniform rotation in the radiation interior. Near the equator the outer layers rotate faster than the inner layers. At mid-latitudes and near the poles, the situation is reversed (Figure 2).

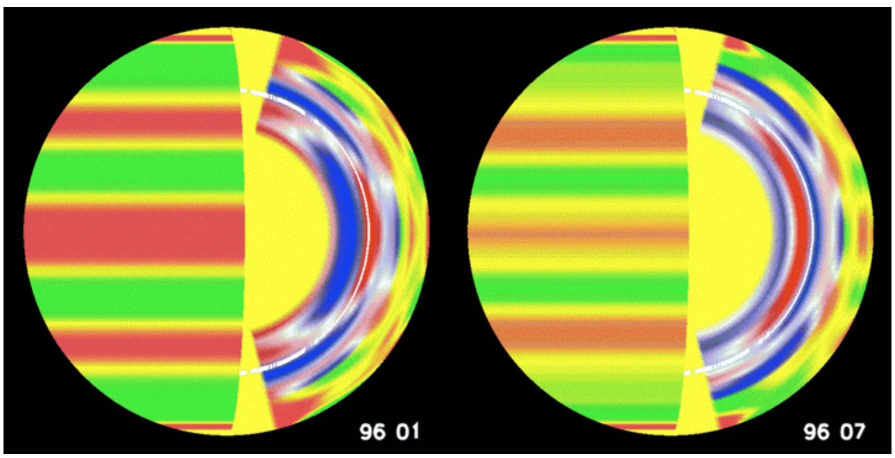

Figure 2. Currents of gas deep inside the Sun pulsate like the blood in human arteries, speeding and slackening every 16 months. Rotation rates near the bottom of the convection zone (white line), the level of the suspected dynamo, change markedly over six months. Faster/slower rates are shown in red/blue. Meanwhile near the surface (seen plainly on the left of each cutaway) bands of faster (red) and slower (green) rotation move towards the equator.

The new results show that the contrast in speed between layers above and below the supposed dynamo region can change by 20 per cent in six months. When the lower gas speeds up, the upper gas slows down, and vice versa. The observations indicate a heartbeat of the Sun at one pulse per 15-16 months in equatorial regions, and perhaps faster at higher latitudes (Figure 3). This result is quite surprising, considering the much longer 11-year period observed in the sunspot cycle, thought to be governed by the same dynamo region. The amplitude of this tachocline oscillation has been greatly reduced since the Sun approached its maximum activity around 2000 (Howe, 2003) and it will be interesting to see if and when it will appear again.

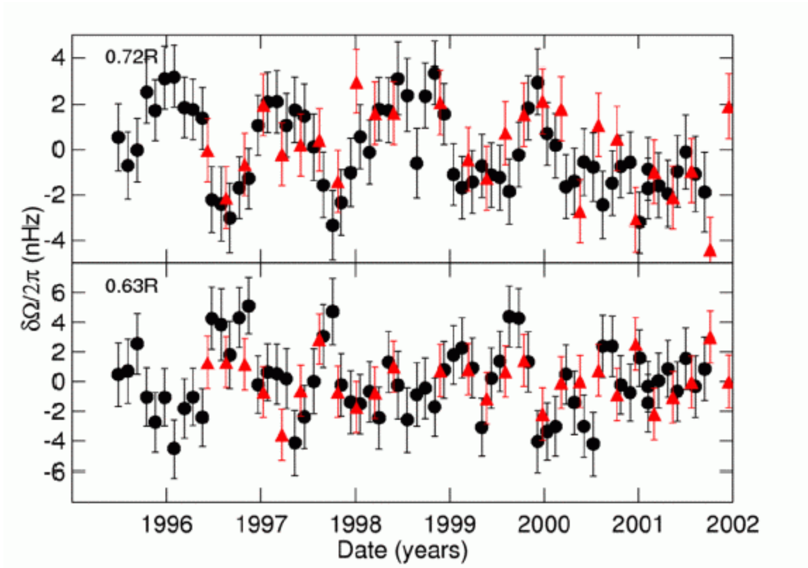

Figure 3. Variation with time of the difference of the rotation rate from the temporal mean at 0.72 R located above the tachocline and at 0.63 R below it, both sampling speeding up and slowing down in the equatorial region. Results obtained from MDI data for two different inversions are shown with red symbols, those from GONG with black symbols (Howe 2003).

The availability of high spatial resolution data from MDI opened a new window to look inside and even right through the Sun. "Time distance helioseismology" or “solar tomography" (Duvall et al., 1993), is a new field in solar research which is developing primarily with MDI data. It is one of the most exciting and most promising techniques for probing the 3-D structure and flows beneath the solar surface and offers the possibility of studying the birth and evolution of active regions below the Sun’s surface and the detection of sunspots on the invisible far side of the Sun. Since spring 2001 the SOHO/MDI team has been making images from the far side of the Sun available routinely to everyone, including the forecasters of space weather. Speeded up by the intense magnetic fields associated with sunspot regions, sound waves reflected from far-side sunspots arrive a few seconds early at he Sun’s near-side face, compared with sound waves from sunspot-free regions (Lindsey & Braun, 2000).

A longstanding problem in solar physics has been to explain how sunspots can last for several weeks without flying apart. Theories have been developed that require inward flows of material that stabilise the structure. The problem: Material often appears to be flowing out of sunspots! 'Time distance helioseismology' has helped shed light on this problem: Just below the surface, the required inward flows are present. We now have the first clear picture of what lies beneath sunspots, the enigmatic, planet-sized dark areas on the surface of the Sun; and have peered inside the Sun to see swirling flows of plasma that create a self-reinforcing cycle which holds a sunspot together (Zhao et al., 2001; Figure 4).

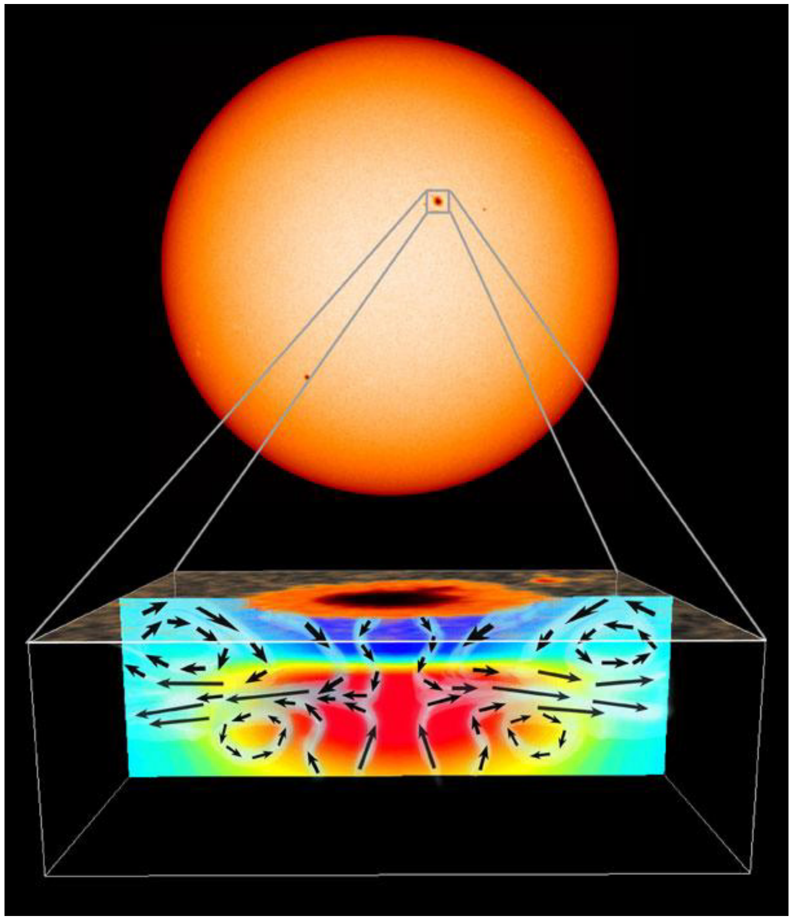

Figure 4. SOHO's MDI reveals subsurface inflows beneath a sunspot. A cross-section going down 12000 kilometres below the surface of the Sun in the vicinity of a sunspot shows a convergence of cool gas (blue) near the surface. This inflow concentrates the magnetic field and suppresses hot gas (red) trying to rise from below. The analysis also revealed that sunspots are surprisingly shallow, changing from cooler to hotter than the surroundings only 5000 km below the surface.

Another SOHO instrument, called SWAN (short for Solar Wind Anisotropies), is also capable of detecting active regions on the far side of the Sun (Bertaux et al., 2000). Mapping 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 (Figure 5). Bertaux et al. (2000) have found that the hydrogen cloud beyond the Sunglows more strongly in the presence of active regions on the far side of the Sun compared to when there are no active regions. The enhanced emission from an active region on the far side of the Sun moves across the sky like a lighthouse beam as the Sun rotates.

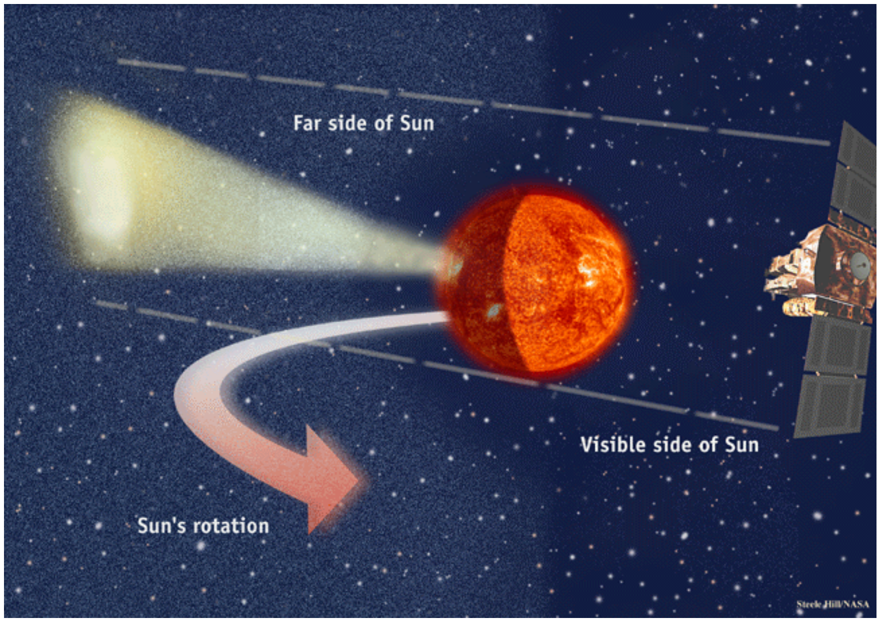

Figure 5. Schematic illustrating SWAN's capabilities of detecting active regions on the far side of the Sun.

The Dynamic Solar Atmosphere

Observations from SOHO and TRACE have replaced the previous view of a quiescent solar atmosphere with a new, extremely dynamic picture. The solar atmosphere undergoes continuouschange on every scale from structures that affects the entire Sun down to tiny loops at the instrument resolution limits. The combination of high spatial, spectral and temporal observations has made it possible to derive three dimensional images of the emission and velocity structures of solar features. These new observations have significantly contributed to a better understanding of the structure of the solar atmosphere. However, at the same time new and interesting challenges arise to interpret and model this highly dynamic and time variable atmosphere.

One of the most puzzling problems in solar physics is the average net redshift of emission lines in the solar transition region. During the last decades, this phenomenon has been observed with several UV instruments with different spatial resolution. Several investigations using precise observations from SUMER have revisited this problem and extended this work to include lines formed at higher temperatures. Peter and Judge (1999) found that the hotter lines show blueshifts.

These recent results suggest that the upper transition region and lower corona appear blueshifted in the quiet Sun, with a steep transition from red- to blue-shifts above 5 $10^{\wedge 5}$ K. This transition from net redshifts to blueshifts is significant because it has major implications for the transition region and solar wind modeling as well as for our understanding of the structure of the solar atmosphere. The results also motivate new laboratory measurements of the wavelengths of hotter lines since the choice of rest wavelengths used to derive these results are crucial for the interpretation of the data.

Active regions have been extensively observed with the EUV instruments on SOHO and recently also by TRACE. In particular, observations of active regions on the solar limb have revealed that loops emitting at transition region temperatures are highly dynamic (e.g. Kjeldseth-Moe and Brekke 1998). Furthermore, large Doppler shifts in active region cool loops (i.e. $T \leq 0.5$ MK) have been reported with line-of-sight velocities reaching ± 100 km s^{-1}. This is a result that challenges existing loop models. In some active regions plasma has been observed to be ejected from the surface. Spike-like jets of material have been observed as well as larger extended ejections of plasma.

Acceleration of the Solar Wind

Coronal hole outflow velocity maps obtained with the SUMER instrument in the Ne VIII emission line at 770Å show a clear relationship between coronal hole outflow velocity and the chromospheric network structure (Figure 6), with the largest outflow velocities occurring along network boundaries and at the intersection of network boundaries (Hassler et al., 1999). This can be considered the first direct spectroscopic determination of the source regions of the fast solar wind in coronal holes.

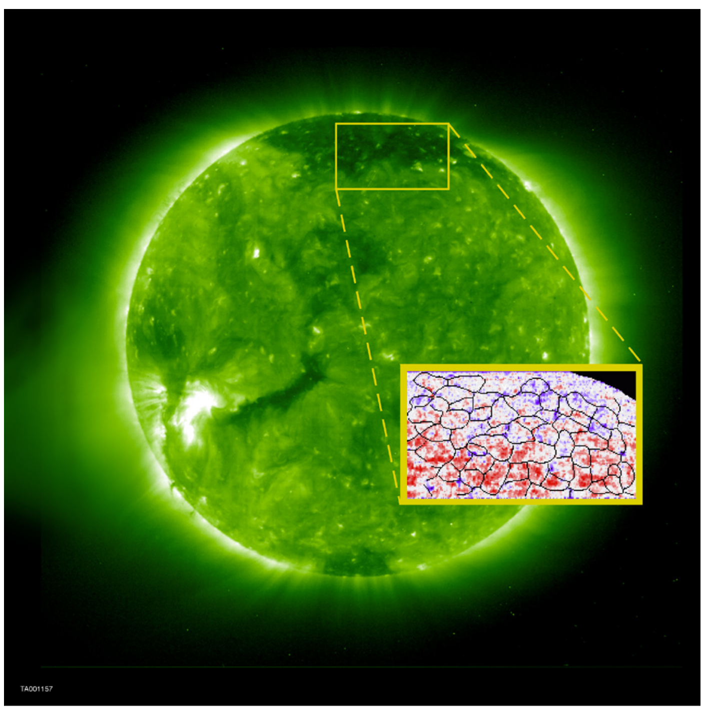

Figure 6. EIT full sun image taken in the emission line of Fe XII 195A, revealing gas at 1.5 million degrees. The "zoomed-in" or "close-up" region shows a Doppler velocity map of plasma at about 630,000 K at the base of the corona, as recorded by SUMER in the Ne VIII emission line at 770Ǎ. Blue represents blue shifts or outflows and red represents red shifts or downflows. The blue regions are inside a coronal hole, or open magnetic field region, where the high speed solar wind is accelerated. Superposed are the edges of "honey-comb" shaped patterns of magnetic fields at the surface of the Sun, where the strongest flows (dark blue) occur.

Proton and O VI outflow velocities in coronal holes have been measured by UVCS using the Doppler dimming method (Kohl et al., 1997; Cranmer et al., 1999). The OVI outflow velocity was found to be significantly higher than the proton velocity, with a very steep increase between 1.5 and 2.5 $R_{\odot}$, reaching outflow velocities of 300 km/s at around 2 $R_{\odot}$. While the hydrogen outflow velocities are still consistent with some conventional theoretical models for polar wind acceleration, the higher oxygen flow speeds cannot be explained by these models. A possible explanation is offered by the dissipation of high-frequency Alfvén waves via gyroresonance with ion cyclotron Larmor motions, which can heat and accelerate ions differently depending on their charge and mass.

Comet Observations

Other instruments on SOHO have proved to be the most prolific comet finders in the history of astronomy. Most of the more than 660 SOHO comet discoveries were made with the Large Angle Spectrometric Coronograph (LASCO) instrument, a set of coronagraphs that view the space around the Sun out to 20 million kilometers (30 $R_{\odot}$), while blotting out the bright solar disk with occulting disks.

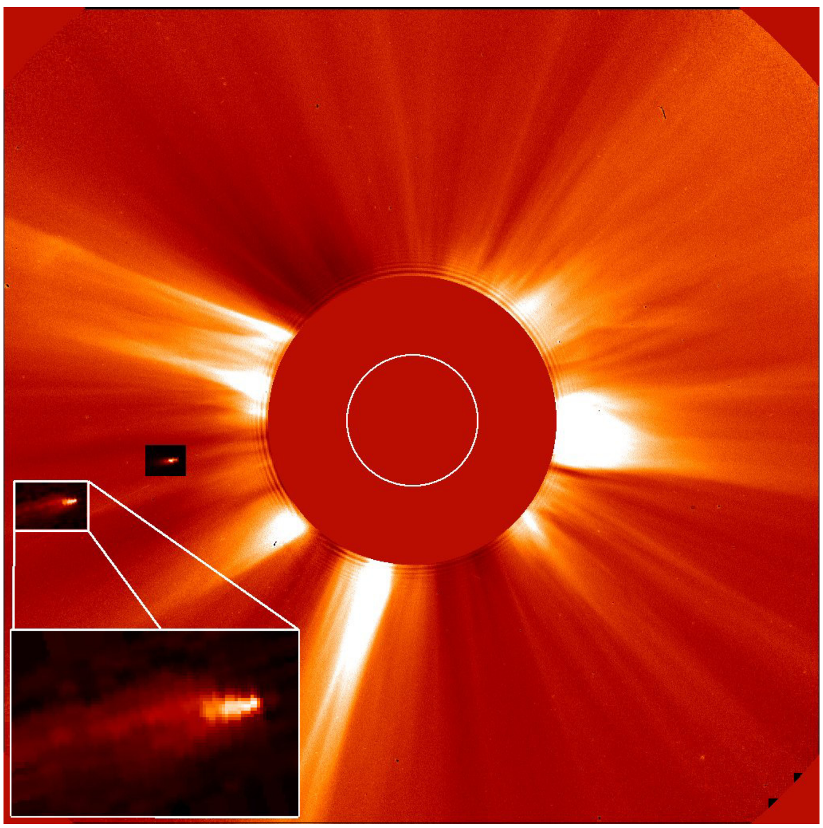

Figure 7. Composite of a LASCO C2 white light image and two UVCS Lyman α images, showing Comet C/2001 C2 (also known as SOHO-294) as it approaches the Sun on 6-7 February 2001. These observations enabled estimates of the outgassing rate and the size of the comet as well as the local density of the solar wind.

Until a few years ago, most of the comets had been discovered by SOHO scientists, but since the images have been freely available on the Internet in almost real-time, the majority of the comets discovered so far have been found by amateur astronomers.

Most comets observed by LASCO are "Kreutz" sungrazers which do not survive their close encounter with the Sun. They are quite small, typically only about 10 m in diameter. They all come from the same direction in space. They are fragments of a huge comet, probably more than 100 km in diameter and well visible even during daylight. Big fragments of this comet were seen by the ancient Greeks, more than 2000 years ago.

Thanks to the near real time operation capabilities of SOHO, UVCS (short for Ultraviolet Coronagraph Spectrometer) has been able to capture the first ever space-based UV spectrometric observations of a comet's tail (Figure 7). SOHO Comet 104 was discovered by LASCO on 9 February 2000 and observed by UVCS at four different heights above the limb the following day. These observations were used to gauge the density of the corona at the position of the comet (Raymond et al., 1998).

When comet Hale-Bopp flew near the Sun in 1997, parading its 100 million kilometres-long tail, it was also observed by the SWAN instrument. The scientists spotted a remarkable feature - never before seen by astronomers - the elongated shadow of a comet tail, more than 150 million kilometers long (Lallement et al., 2002). Water-ice in the comet's nucleus began to vaporise as Hale-Bopp approached the Sun. As expected, the Sun's ultraviolet radiation split the water molecules, liberating a cloud of hydrogen atoms that glow in the ultraviolet light. As the distance between the comet and the Sun quickly decreased, the release of vapour from the nucleus and the consequent production of hydrogen increased. As a result, in a huge, 10 million kilometre-wide region around the nucleus, the comet absorbed most of the ultraviolet light coming from the Sun. Thus, the comet projected a distinct shadow on the hydrogen haze of the Solar System. For an imaginary ultraviolet-eyed onlooker situated on the side of the comet opposite the Sun, it would have been a perfect opportunity to observe a total solar eclipse by a comet!

When Comet Wirtanen, made its most recent periodic visit to the Sun, it pumped out water vapour at a rate of 20,000 tons a day, according to the SWAN data. For the great Comet Hale-Bopp the rate reached 200 million tons a day, and SWAN watched its hydrogen cloud grow to 100 million kilometres - by far the largest object ever seen in the Solar System (Combi et al., 2000).

The SWAN instrument also observed the break-up of Comet LINEAR (Mäkinen et al., 2001). The total amount of water vapour observed by SWAN from 25 May to 12 August 2000 was estimated at 3.3 million tons. 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 of the fragments. Combining the two numbers give 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.

Such observations illustrate how SOHO, in addition to giving us new information about the Sun, is expanding our knowledge about the inner solar system and the physics of comets.

Coronal Mass Ejections

The Large Angle Spectrometric Coronagraph (LASCO) takes images of the solar corona by blocking the light coming directly from the Sun itself with an occulter disk, creating an artificial eclipse within the instrument. LASCO best observes limb CMEs, but its excellent sensitivity also allows unprecedented detection of halo CMEs.

LASCO has been collecting an extensive database for establishing the best statistics ever on CMEs and their geomagnetic effects. By June 2003 more than 6000 CMEs have been recorded[*]. CME's are vast structures of plasma and magnetic fields that are expelled from the Sun. CMEs moving outward from the Sun along the Sun-Earth line can, in principle, be detected when they have expanded to a size that exceeds the diameter of the coronagraphs occulting disk. CME's directed toward or away from the Earth should appear as expanding halo-like brightenings surrounding the occulter.

Although halo CMEs were discovered by the SOLWIND coronagraph two solar cycles ago (Howard et al., 1982) the LASCO experiment is the first to observe a significant number of these events, thanks to its extended field of view and its improved sensitivity compared with earlier coronagraphs.

An extensive survey of CME observations from SOHO shows that the CME rate increases by an order of magnitude from 0.5/day at solar minimum to 6/day at solar maximum (Gopalswamy et al, 2003). This rate is almost twice the rates estimated from previous cycles. Another interesting feature is that the maximum CME rate peaked about 2 years after the peak of the sunspot number as can be seen in Figure 8.

[*] A complete list of all detected CMEs with LASCO can be found at: http://lasco-www.nrl.navy.mil/cmelist.html

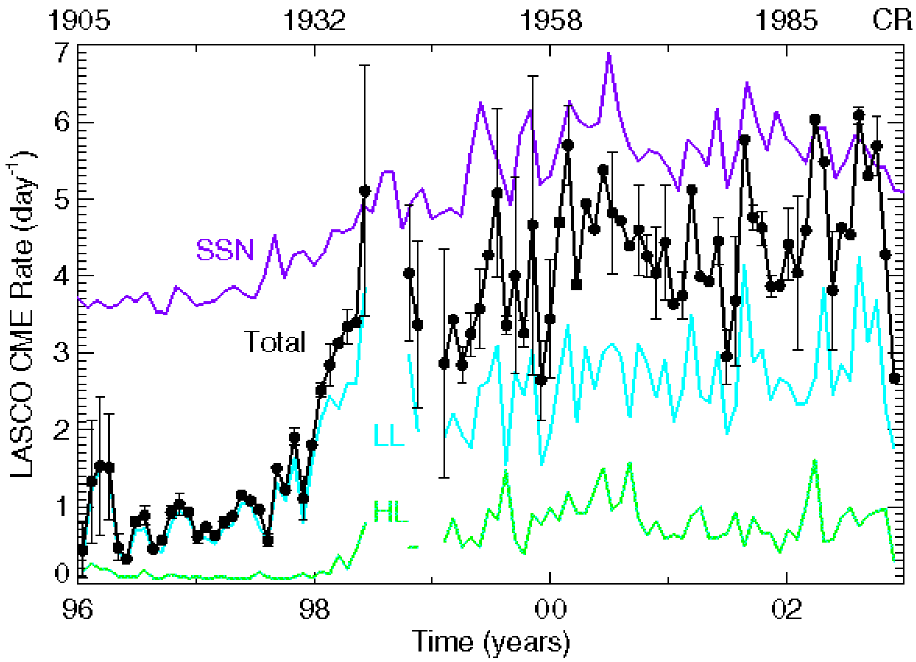

Figure 8. Comparison between low-latitude (LL), high-latitude (HL) and total (black) rates of CME's as a function of time. The sunspot number (SSN) is also shown (from Gopalswamy et al 2003).

<u>Space weather forecasting</u>

The response of the space environment to the constantly changing Sun is known as "space weather". Most of the time space weather is of little concern in our everyday lives. However, when the space environment around the Earth is disturbed by the variable outputs of the Sun, technologies that we depend on can be affected.

Our society is much more sensitive to space weather activity today than was the case during the last solar maximum in 1991. An example is the possible disruption of satellites. We depend on satellites for weather information, communications, navigation, exploration, search and rescue, research, and defense systems. Thus, the impact of satellite system failures is more far-reaching than ever before, and the trend will almost certainly continue at an increasing rate. Furthermore, safe operation of the International Space Station depends on timely warnings of eruptions on the Sun.

Two instruments on SOHO have proved to be especially valuable for continuous real-time monitoring of solar storms that affect space weather. One is the Extreme Ultraviolet Imaging Telescope (EIT) that provides images of the solar atmosphere at four wavelengths, revealing flares and other stormy events in the atmosphere.

The other is LASCO (see section on comets above), which was designed to detect and study coronal mass ejections (CMEs). CMEs that are heading towards Earth are causing some of the most dramatic space weather effects. Figure 9 shows one of the most dramatic eruptions recorded by SOHO. As this event was directed towards the side and not towards Earth, it had no effect in geospace.

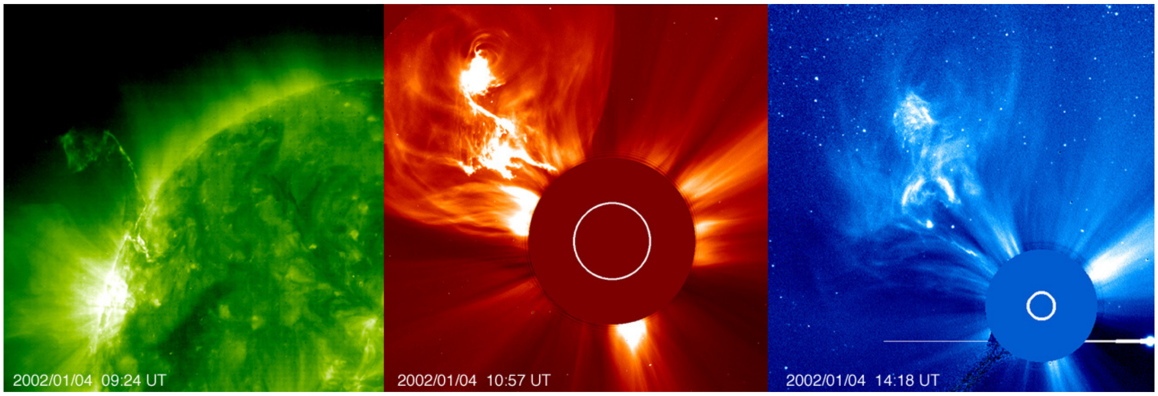

Figure 9. A spectacular Coronal Mass Ejection (CME) taking off from the Sun on 4 January 2002, starting off as a filament eruption seen by EIT in Fe XII 195 Å. The complexity and structure of the CME as it passed through the LASCO C2 and C3 fields of view amazed even experienced solar physicists at the SOHO operations center.

SOHO has proved to be an important tool in monitoring eruptions from the Sun that causes effects on the Earth. Before SOHO was operational the accuracy in forecasting geomagnetic disturbances was fairly poor. The Space Weather Operations Center at the Space Environment Center (SEC) in Boulder uses SOHO images daily. The forecast operations have become to rely on SOHO on a routine basis as a key input to solar observing and geomagnetic forecasting. LASCO provides the only direct observation of coronal mass ejections. Prior to LASCO they had to rely on activity they knew to be well associated with CMEs, but none of these associations are 100% reliable. They use direction, size, and velocity information in LASCO images to help determine the arrival time and effectiveness of the disturbance.

EIT also plays an important role at SEC to pin down the source of any eruption. In addition EIT is a very good source for identifying erupting prominences and to identify coronal hole locations. Coronal holes have become an increasingly important part of the geomagnetic forecasting process. In fact at this point in the solar cycle coronal hole activity has become the predominant driver of geomagnetic activity.

Total Solar Irradiance Variations

The VIRGO instrument on SOHO extends the record of total solar irradiance (TSI) measurements into cycle 23 (Quinn & Fröhlich, 1999). In Figure 10 measurements from six independent space-based radiometers since 1978 (top) have been combined to produce the composite TSI over two decades (bottom). They show that the Sun's output fluctuates during each 11-year sunspot cycle, changing by about 0.1% between maxima (1980 and 1990) and minima (1987 and 1997) of solar activity. Temporary dips of up to 0.3% and a few days duration are the result of large sunspots passing over the visible hemisphere. The larger number of sunspots near the peak in the 11-year cycle is accompanied by a general rise in magnetic activity that creates an increase in the luminous output that exceeds the cooling effects of sunspots.

Offsets among the various data sets are the direct result of uncertainties in the absolute radiometer scale of the radiometers (±0.3%). Despite these biases, each data set clearly shows varying radiation levels that track the overall 11-year solar activity cycle.

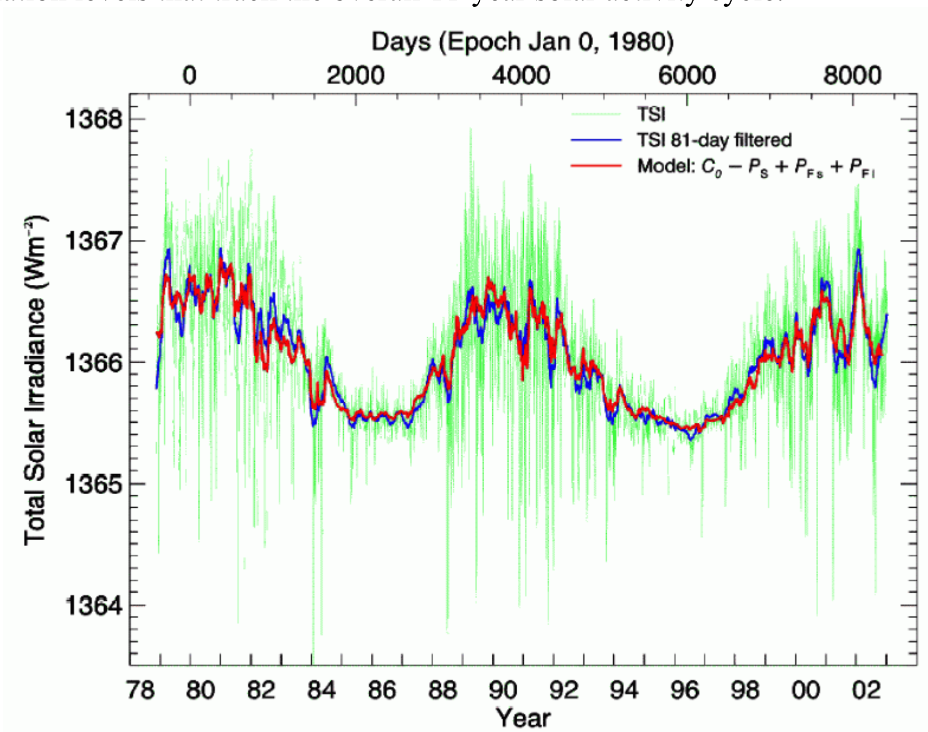

Figure 10. Daily values of total solar irradiance from 1978 to present. The data labeled TSO are a composite of observations from HF on NIMBUS-7, ACRIM-I on SMM, ACRIM-II on UARS and from VIRGO radiometers on SOHO. The blue line shows the 81-day smooted values. For comparison, the 81-day filtered proxy model (red curve) from Fröhlich and Lean (2002).

Conclusions

SOHO was set out to tackle three broad topics in solar and heliospheric physics: the structure and dynamics of the solar interior, the heating and dynamics of the solar corona, and the acceleration and composition of the solar wind. In all three areas, observations from SOHO have caused great strides in our understanding of the diverse physical processes at work in our Sun. This has been made possible by the comprehensive suite of state of the art instruments mounted on the superb and stable platform of the SOHO spacecraft, placed in the unique vantage point of the L1 halo orbit.

In complex areas of research such as solar physics, progress is not made by just a few people acting in a vacuum. 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 effort. The interplay between theory and observations has given many new insights and will continue to do so for many years. With the treasure of SOHO data already in the SOHO archive (and many more data yet to come), we should be able to unravel even more mysteries of the closest star.

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