2.6 SOHO

The Solar and Heliospheric Observatory (SOHO) is a project of international cooperation between ESA and NASA to study the Sun, from its deep core to the outer corona and the solar wind. Unique data from three helioseismology instruments (GOLF, VIRGO and MDI/SOI) are providing new insights into the structure and dynamics of the solar interior, from the deep core to the outermost layers of the convection zone. Six remote sensing instruments (SUMER, CDS, EIT, LASCO, UVCS and SWAN) are providing exciting new data on a wide range of topics, such as transition region dynamics, coronal plumes, coronal holes, streamers and coronal mass ejections, giving us our first comprehensive view of the outer solar atmosphere and corona. These data are complemented by in-situ measurements of the solar wind and energetic particles by three particle experiments (CELIAS, COSTEP and ERNE).

A summary of SOHO's 12 instruments, which represent the most comprehensive set of solar and heliospheric instruments ever developed and carried on the same platform, is presented in Table 2.6.1.

Mission status

SOHO was launched by an Atlas IIAS from Cape Canaveral Air Station on 2 December 1995, and was inserted into its halo orbit around the L1 Lagrangian point on 14 February 1996, 6 weeks ahead of schedule. From this vantage point, it is continuously monitoring the Sun, the heliosphere and the solar wind particles that stream toward the Earth. Commissioning of the spacecraft and its scientific payload was completed by the end of March 1996. The launch was so accurate and the orbital manoeuvres were so efficient that there remains sufficient propellant to maintain the halo orbit for several decades, several times the 6 years originally anticipated. All of the instruments and the spacecraft itself are in excellent condition and engineering evaluations indicate they will continue to operate for at least the next 5 years.

ESA's Science Programme Committee, at its 79th meeting on 18/19 February 1997 in Paris, unanimously approved the extension of the SOHO mission for a period of 5 years beyond its nominal lifetime, i.e. until March 2003.

Detailed information on the mission status, including the latest images from the Sun, as well as daily observing plans and targets are available under the SOHO home page on the Internet at http://sohowww.nascom.nasa.gov/operations/

Operations

The SOHO Experiment Operations Facility (EOF), at NASA's Goddard Space Flight Center (GSFC), is the focal point for mission science planning and instrument operations. At the EOF, the experiment teams receive realtime and playback flight telemetry data, process these data to determine instrument commands, and send commands directly from their workstations to their instruments, both in near-realtime and with delayed execution.

It should be emphasised that SOHO Science is more than the sum of the efforts from each experiment. From the very beginning, the SOHO experiments have devoted much of their observing time to Joint Observing Programs (JOPs), tackling specific physical problems, such as the temperature and density structure in coronal holes, through coordinated observations between SOHO experiments, with other spacecraft, such as Yohkoh and Ulysses, and with numerous ground-based observatories around the world. In a typical SOHO week, 3-5 different JOPs may be run, each one several times. As of 31 December 1997, the SOHO campaign catalogue (http://sohowww.nascom.nasa.gov/cgi-bin/soho_campaign_search) lists 107 campaigns with ground-based observatories and 42 joint observing campaigns with Yohkoh, respectively.

For further information on SOHO, see http://sohowww.estec.esa.nl

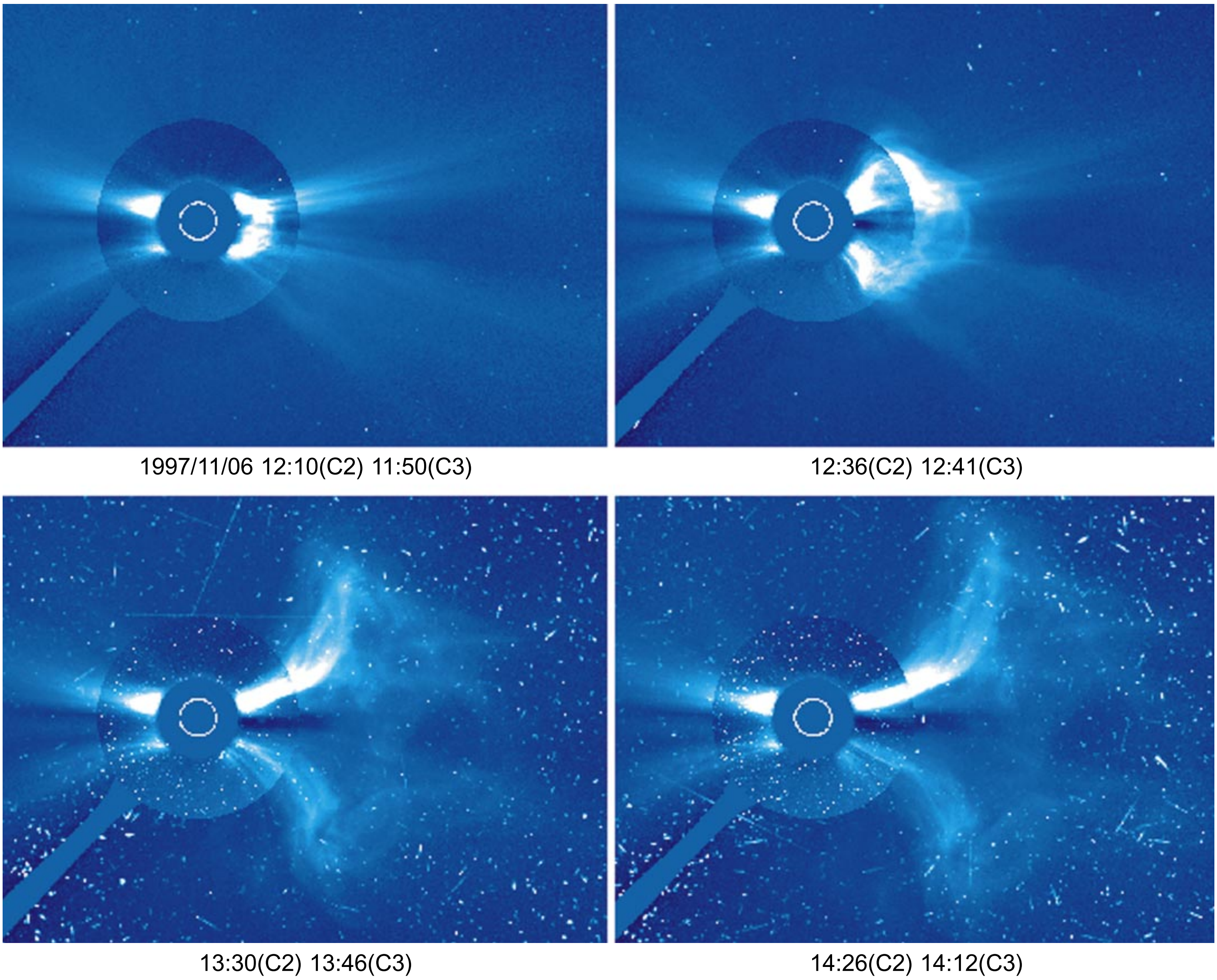


Figure 2.6.1. Development of the large coronal mass ejection (CME) of 6 November 1997 as recorded by the C2 and C3 coronagraphs of SOHO's LASCO instrument. The CME originated from the site of an X-9.4 flare, approximately 30° off the Sun's west limb. The numerous bright points and streaks in the two lower images are caused by high-energy (E>100 MeV) protons accelerated at the site of the flare. The small white circle in the centre of the images indicates the size of the Sun.

Data archive

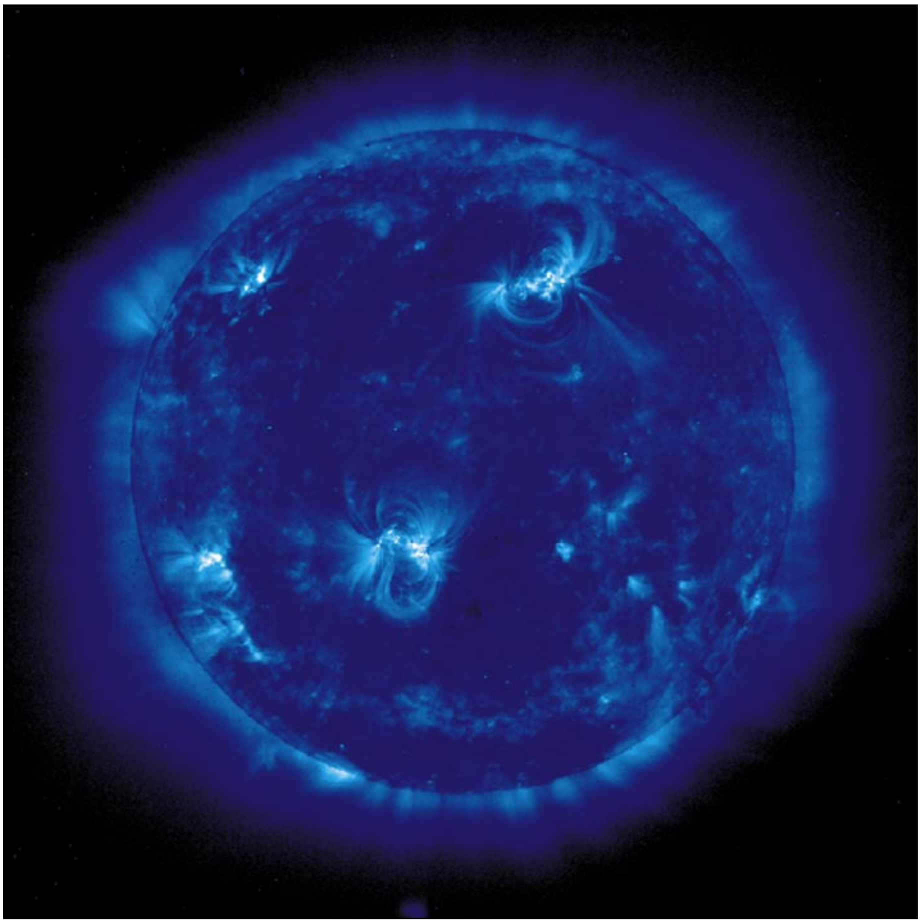
A SOHO archive has been established at the EOF, and three subsidiary archives are being developed in Europe (Institut d'Astrophysique Spatial in Orsay, France; Rutherford Appleton Laboratory, UK; and University of Torino, Italy). Perhaps a better term is data libraries, as they provide a platform for SOHO-wide data analysis, using integrated software, as the data come down from the spacecraft. As of 1 March 1998, the SOHO archive held a total of 322 Gbytes.

Although it was not envisaged in 1988, the World Wide Web has allowed SOHO data to be widely and almost instantaneously distributed to the international scientific community, students and general public. Outreach has been raised to a new level. By

Table 2.6.1. Instruments in the SOHO payload.

Investigation	*Principal Investigator*	*Collaborating Countries*	*Measurements*	*Technique*
Helioseismology				
Global Oscillations at Low Frequencies (GOLF)	A. Gabriel, IAS, Orsay, F	F , ESA, DK, D, CH, UK, NL, E, USA	Global Sun velocity oscillations (l=0-3)	Na-vapour resonant scattering cell, Doppler shift and circular polarisation
Variability of solar IRradiance and Gravity Oscillations (VIRGO)	C. Fröhlich, PMOD/WRC, Davos, CH	CH, N, F, B, ESA, E	Low-degree (l =0-7) irradiance oscillations and solar constant	Global Sun and low-resolution (12-pixel) imaging and active cavity radiometers
Michelson Doppler Imager (MDI)	P.H. Scherrer, Stanford Univ, California, USA	USA, DK, UK	Velocity oscillations high-degree modes (up to l=4500)	Doppler shift with Fourier tachometer, 4 and 1.3 arcsec resolution
Solar Atmosphere Remote Sensing				
Solar UV Measurements of Emitted Radiation (SUMER)	K. Wilhelm, MPAe, Lindau, D	D, F, CH, USA	Plasma flow characteristics (temperature, density, velocity); chromosphere through corona	Normal-incidence spectrometer, 50-160 nm, spectral resolution 20000-40000, angular resolution 1.2-1.5 arcsec
Coronal Diagnostic Spectrometer (CDS)	R.A. Harrison, RAL, Chilton, UK	UK, CH, D, USA, N, I	Temperature and density: transition region and corona	Normal and razing-incidence spectrometers, 15-80 nm, spectral resolution 1000-10000, angular resolution 3 arcsec
Extreme-ultraviolet Imaging Telescope (EIT)	J-P Delaboudinière, IAS, Orsay, F	F, USA, B	Evolution of chromospheric and coronal structures	Full-disc images (1024×1024 pixels in 42×42 arcmin) at lines of HeII, FeIX, FeXII, FeXV
Ultraviolet Coronagraph Spectrometer (UVCS)	J.L. Kohl, SAO, Cambridge, MA, USA	USA, I, CH, D	Electron and ion temperature densities, velocities in corona (1.3-10 R_u)	Profiles and/or intensity of selected EUV lines between 1.3 and 10 R_u
Large Angle and Spectrometric COronagraph (LASCO)	G. Brueckner NRL, Washington DC, USA	USA, D, F UK	Structures' evolution, mass, momentum and energy transport in corona (1.1-30 R_u)	One internally and two externally occulted coronagraphs. Spectrometer for 1.1-3 R_u
Solar Wind ANisotropies (SWAN)	J.L. Bertaux, SA Verrières-le-Buisson, F	F, SF, USA	Solar wind mass flux anisotropies. Temporal variations	Scanning telescopes with hydrogen absorption cell for Lyman-alpha
Solar Wind 'in situ'				
Charge, ELement and Isotope Analysis System (CELIAS)	P. Bochsler, Univ. Bern, CH	CH, D, USA, Russia	Energy distribution and composition. (mass, charge, charge state) (0.1-1000 keV/e)	Electrostatic deflection, time-of-flight measurements and solid-state detectors
Comprehensive SupraThermal Energetic Particle analyser (COSTEP)	H. Kunow Univ. Kiel, D	D, USA, J, F, E, ESA, IRL	Energy distribution of ions (p, He) 0.04-53 MeV/n and electrons 0.04-5 MeV	Solid-state detector telescopes and electrostatic analysers
Energetic and Relativistic Nuclei and Electron experiment (ERNE)	J. Torsti, Univ. Turku, SF	SF, UK	Energy distribution and isotopic, composition of ions (p-Ni) 1.4-540 MeV/n and electrons 5-60 MeV	Solid-state and plastic scintillation detectors

Figure 2.6.2. SOHO-EIT image in resonance lines of eight- and nine-times ionised iron (FeIX/X) at 171 Å in the extreme UV, showing the solar corona at a temperature of about 1 million K. This image was recorded on 11 September 1997. It is dominated by two large active region systems, composed of numerous magnetic loops.



typing http://sohowww.nascom.nasa.gov/ anyone anywhere on the Internet has immediate access to the daily SOHO data base as well as to a wealth of information that includes current images, solar movies, observing plans, details of the mission and descriptions of the instruments. Web tools allow anyone access to the record of SOHO observations and the means to request scientific data. The SOHO Data Archive is operational at GSFC and copies are in various stages of development in Europe at the three subsidiary archives.

Scientific highlights

Solar interior

The SOHO helioseismology experiments (GOLF, VIRGO, MDI), while patiently pursuing their holy grail of detecting solar gravity modes, have produced p-mode spectra cleaner by at least an order of magnitude than achieved from the ground. Some of the highlight results from the analysis of these data can be summarised as:

— Applying a new technique, called time-distance helioseismology, to high-resolution MDI data provided the first-ever image of a star's convection zone, showing the first maps of vertical and horizontal flow velocities as well as sound speed variations in the convection zone just below the visible surface.

— MDI, GOLF and VIRGO data have provided the most precise measurements of the sound speed profile and the (differential) rotation profile within the Sun.

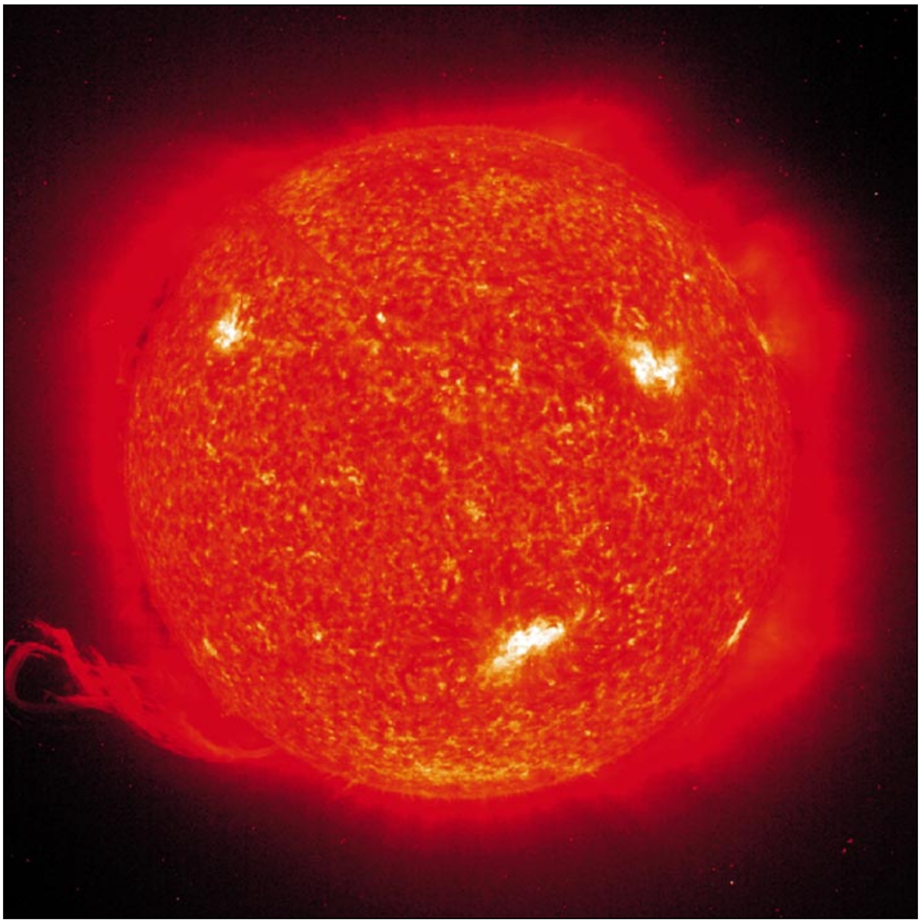
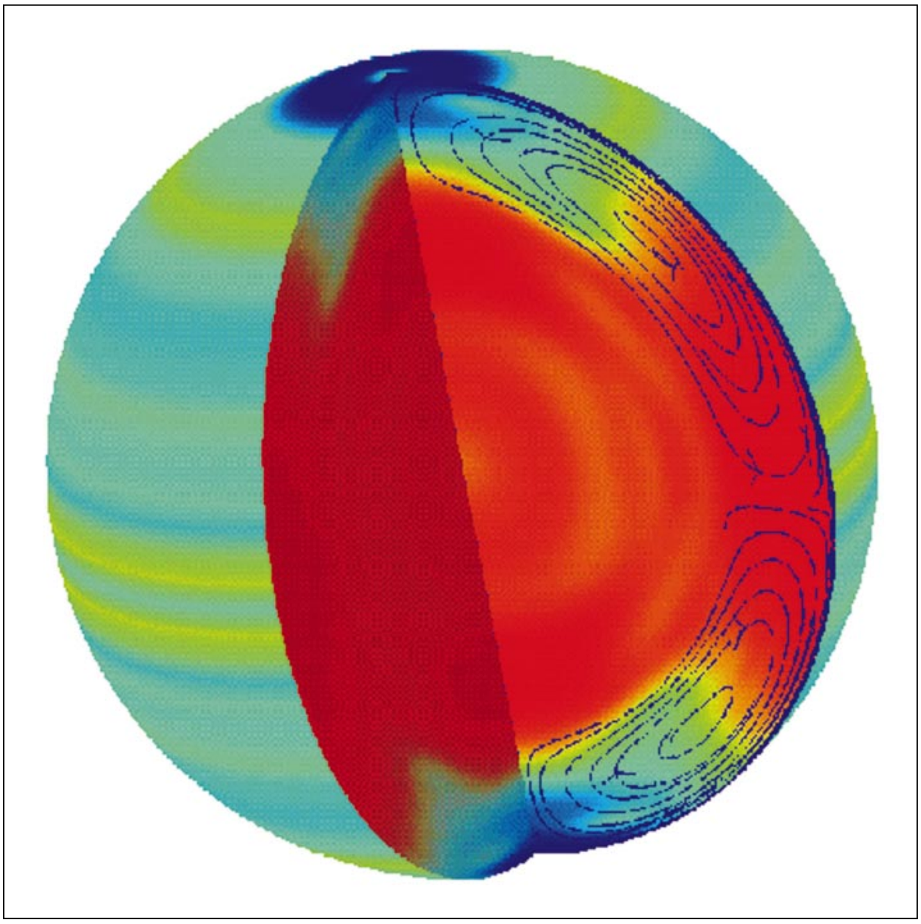


Figure 2.6.3. SOHO-EIT image from 14 September 1997 showing a huge eruptive prominence in the resonance line of singly ionised helium (HeII) at 304 Å in the extreme ultraviolet. The material in the eruptive prominence is at temperatures of 60 000-80 000 K, much cooler than the surrounding corona, which is typically above 1 million K.

— MDI data have revealed a jet-like flow near the poles, which is totally inside the Sun and cannot be seen at the surface. Ringing the Sun at about 75° latitude, this flow consists of a flattened oval region about 30 000 km across where material moves about 10% faster than its surroundings.
— MDI data revealed belts in the northern and southern hemispheres where currents flow at different relative speeds. Six of these bands move slightly faster than their surrounding material. These belts are more than 65 000 km across and they contain 'winds' that move at about 15 km/h relative to their surroundings.
— Applying the new time-distant helioseismology technique to MDI data, researchers demonstrated that the Sun's entire outer layer , to a depth of at least 25 000 km, is steadily flowing from the equator to the poles. The rate is relatively low, about 80 km/h, compared to its rotation speed of about 7200 km/h, but it is sufficient to complete the journey in a little more than a year
— High-precision MDI measurements of the Sun's shape and brightness obtained during two special 360° roll manoeuvres of SOHO have produced the most precise determination of solar oblateness ever. There is no excess oblateness. These measurements unambiguously rule out the possibility of a rapidly rotating core, and any significant solar cycle variation in the oblateness.
— Results from the radiometers and photometers of VIRGO confirm that active regions modulate total and spectral irradiance on time scales of days to weeks.

Figure 2.6.4. The cutaway reveals rotation speeds inside the Sun. The large dark red band is a massive fast flow of plasma beneath the solar equator. Additionally, a newly discovered, but much more subtle plasma stream can be seen in the cutaway at the poles. They are the light blue areas embedded in the slower-moving dark blue regions. Finally, the blue lines in the cutaway at the right represent the surface flow from the equator to the poles, which, as SOHO observations have revealed for the first time, extends to a depth of at least 26 000 km (4% of the solar radius), so that it is likely to be an important factor in solar dynamics, although the flow speed (10-20 m/s) is small compared to random motions at the surface (1 km/s). The return flow indicated at the bottom of the convection zone is from a simple model and has not yet been observed.



Solar corona and solar wind

SOHO's coronal instruments have yielded a bonanza of observations of a quality far superior to their predecessors, generating both new results and confirmations of hitherto hard-to-establish conjectures on the solar atmosphere. These observations have already substantially improved our insights into the physics of the Sun itself as well as how the solar wind and solar coronal eruptions influence the near-Earth environment. Some of the results can be briefly summarised as:

— The UVCS coronagraph has revealed extremely broad line profiles of HI (neutral hydrogen) atoms and minor ions such as OVI and MgX. Also, the OVI motions are found to be highly anisotropic, implying kinetic temperature anisotropies of $T_{\wedge}/T_{||}>100$. These findings provide strong evidence for MHD wave heating via ion-cyclotron resonance.

— A team that has combined Doppler-dimming measurements made by UVCS and LASCO white light images of the solar corona with radio scintillation measurements by the Galileo spacecraft, has proposed a new view of the origins of the slow and fast solar wind. While the prevailing view is that the fast solar wind originates only in polar coronal holes and their equatorial extensions, the new measurements are interpreted as evidence of a scenario in which the slow solar wind is limited to the axes (or 'stalks') of coronal streamers and the fast solar wind dominates the corona.

— SOHO's CDS and SUMER spectroheliometers observe extensive evidence of explosive events in transition region lines. These could be the signature of magnetic reconnection events associated with localised small magnetic dipoles that appear in magnetogrammes obtained by MDI near the base of many of the explosive events studied. These events, called 'blinkers', are being further investigated for their role in transition region and local coronal heating.
— Coordinated measurements by SUMER and CDS have provided new observational data concerning the temperature structure in coronal holes, the places that are commonly believed to be the origin of the high-speed wind streams. The electron temperature measured in holes starts at the base at a higher value than expected, of the same order as for closed field regions (about 1 MK). The temperature, however , falls much more rapidly with height than had been expected, reaching only about 0.3 MK at 1.3 solar radii. This clearly rules out a thermally-driven fast solar wind.
— The LASCO instrument is collecting an extensive database for establishing firm statistics on Coronal Mass Ejections (CMEs) and their geomagnetic effects, and on sources of the solar wind for both the quiet wind and the high-speed streams.
— EIT and LASCO have recorded several Earth-directed CMEs, several of which actually hit the Earth's magnetosphere. One can expect that SOHO's remote sensing instruments, together with its solar wind observations (in particular CELIAS) and other solar-terrestrial spacecraft (Wind, Polar, etc), will provide a new class of observations for space weather forecasters during the rising phase of the next solar maximum.

Solar wind and energetic particles
The in-situ particle detectors (ERNE and COSTEP) regularly detect high energy protons, electrons and alpha particles in the aftermath of filament eruptions and CMEs, while CELIAS, SOHO's solar wind analyser, has doubled the number of elements and isotopes previously recorded in the solar wind. During a Venus passage through a very close inferior conjunction with the Sun, CELIAS also observed, for the first time from such a large distance, pick-up ions from Venus' ionosphere, finding a much smaller diffusion cone than expected. SWAN, the solar wind anisotropy detector, has recorded the first full-sky Lyman-alpha maps at a resolution and signal to noise ratio of at least a factor 10 better than previous observations. From these maps, the latitude distribution of the solar wind can be determined.

A SOHO bibliography and publications database is available via the Internet at: http://sohowww.nascom.nasa.gov/bibliography/