

# AN OVERVIEW OF SOHO 12 YEARS LATER

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**Abstract:** The Solar and Heliospheric Observatory SOHO was launched on 1995 December 2 and completed launch and early orbit activities (commissioning) in 1996 March, reaching its L1 halo orbit. The control of the spacecraft was lost in 1998 June, and only restored three months later through the heroic efforts of an ESA-NASA-contractor-university team. All twelve scientific instruments were still usable, most with no ill effects. Despite the immediate failure of two of the three onboard gyroscopes and the later demise of the third (in 1998 December), by 1999 February, new, gyroless, onboard control software not only allowed the spacecraft to return to full scientific usefulness, but actually provided a greater margin of safety for spacecraft operations. SOHO's current margins for thruster propellant and solar panel output are considered by spacecraft engineers to be adequate to extend its operational life longer than 2010. Some of the scientific insights from SOHO and scientific topics for future are reviewed in the following lines.

**Keywords:** Solar Energetic Particles – SOHO satellite – Solar Physics – Solar Terrestrial Physics.

## 1 Introduction

The Solar and Heliospheric Observatory (SOHO) celebrates its 12th launch anniversary on December 2. In late 1996, shortly after its launch, SOHO was able to observe the last minimum of the roughly 11-year activity cycle of the Sun. The minimum was followed by a rapid rise in solar activity, peaking 2001 and 2002. Activity levels have slowly declined since then, but we haven't reached solar minimum yet, despite passing 11.1 years since the last minimum (the average length of a solar cycle, Figure 1).

SOHO, the Solar and Heliospheric Observatory, is an international cooperative project by ESA and NASA to study the Sun, from its deep core to the outer corona,

and the solar wind. It carries a complement of twelve sophisticated instruments developed and furnished by 39 institutes from fifteen countries (Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Japan, The Netherlands, Norway, Russia, Spain, Switzerland, United Kingdom, and the United States).

Primary scientific objectives of SOHO satellite are:

- Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments;
- explore the fundamental properties of plasma systems; and
- define the origins and impacts of variability in the Sun-Earth system.

SOHO science is rooted in all three of these objectives.

Solar Interior are sonded by SOHO with heliosismology instrumentation:

- GOLF: Global Oscillations at Low Frequencies;
- VIRGO: Variability of Solar Irradiance and Gravity Oscillations; and
- MDI: Michelson Doppler Imager.

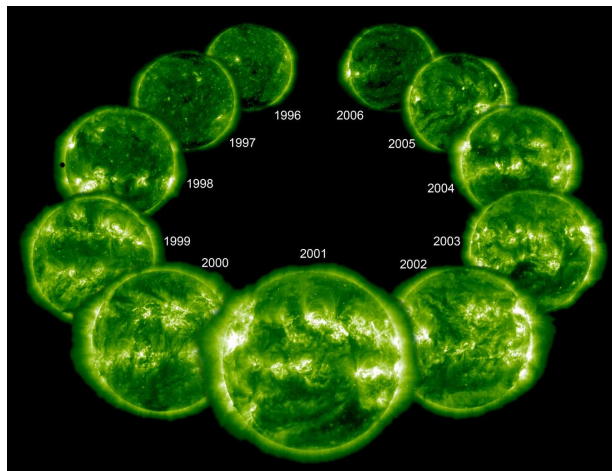


Figure 1: An EIT image from each year of nearly an entire solar cycle assembled by Steele Hill (NASA GSFC).

Solar atmosphere (Photosphere, Chromosphere and Corona) are directly observed in several region of the electromagnetic spectrum with:

- SUMER: Solar Ultraviolet Measurements of Emitted Radiation;
- CDS: Coronal Diagnostic Spectrometer;
- EIT: Extreme-Ultraviolet Imaging Telescope;
- UVCS: Ultra-Violet Coronagraph Spectrometer; and
- LASCO: Large-Angle Spectroscopic Coronagraph.

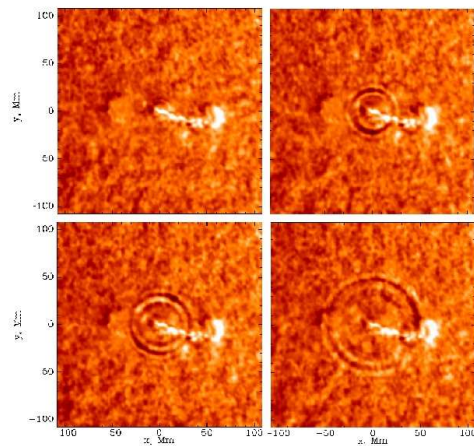


Figure 2: Scientists have shown for the first time that solar flares produce seismic waves in the Sun's interior that closely resemble those created by earthquakes on our planet. The researchers observed a flare-generated solar quake that contained about 40,000 times the energy released in the great earthquake that devastated San Francisco in 1906

Finally, solar wind and solar energetic particles are analysed with particle instrumentation on board SOHO:

- CELIAS: Charge, Element and Isotope Analysis System;
- SWAN: Solar Wind Anisotropies;
- COSTEP: Comprehensive Supra-Thermal and Energetic-Particle Analyser, with two instruments: LION (Low Energy Ion and Electron Instrument) and EPHIN (Electron, Proton Helium Instrument); and

- ERNE Energetic and Relativistic Nuclei and Electron Experiment also with two instruments: LED (Low Energy Detector) and HED (High Energy Detector).

SOHO has improved our understanding of the Sun since its launch. It has provided the first images of structures and flows below the surface of the Sun 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.

SOHO findings are documented in 2500 papers since its launch, representing the work of 2300 scientists, approximately. 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.

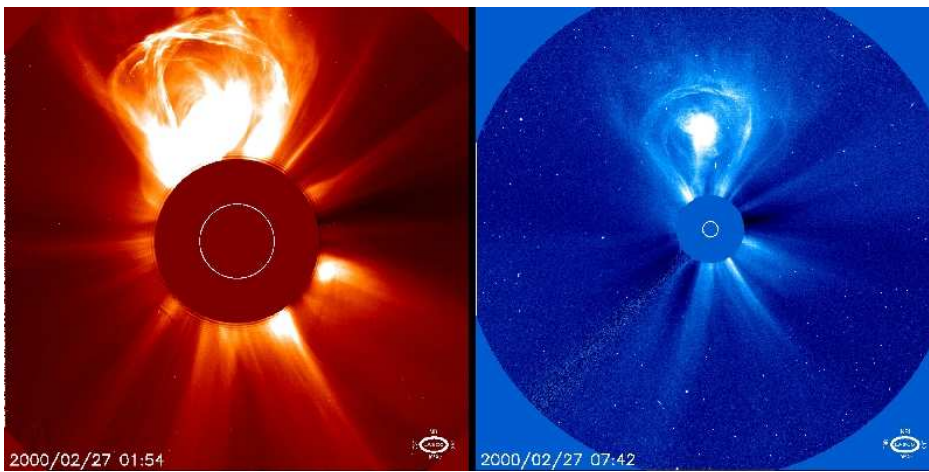


Figure 3: A coronal mass ejection on Feb. 27, 2000 taken by LASCO C2 and C3. A CME blasts into space a billion tons of particles travelling millions of miles an hour. This particular CME is “lightbulb-shaped”.

## 2 Scientific insights from SOHO

Among the scientific insights obtained from SOHO we can briefly enumerate a lot of advances in the following topics:

## 2.1 The Solar Interior and Total Irradiance

**Total solar irradiance variations.** VIRGO radiometers takes the dose of radiation over 12 years including a complete solar cycle. The total solar irradiance (TSI) obtained with the VIRGO experiment [1] makes possible the first independent and internally consistent determination of possible long-term changes, such as degradation. Interpretation of the TSI record, whether as a steady cycle with no underlying secular change or as showing an increasing trend, has broad social and political impacts as governments make decisions on their responses (if any) to global warming.

**Constraints on solar abundances.** The recent measurements on abundances of heavy elements [2], [3] have led to significant changes in our understanding of the internal structure and constitution of the Sun. Standard solar models calculated with the new abundances are significantly different from the helioseismic results which were in a good agreement with the previous solar models [2]. This discrepancy affects the predicted neutrino fluxes [4], [5].

**Rotation of the deep interior.** Analyzing SOHO GOLF data in this way, [6] obtain results that are consistent with a flat solid-body rotation rate of the inner layers down to around  $0.2 R_{Sun}$ . No g-modes have yet been positively identified, although some candidates have been found in the GOLF observations.

**Solar-cycle variations in the size of the Sun.** The MDI data analysis made that Dziembowski and Goode [7] concluded that the Sun becomes smaller and cooler at solar maximum. By contrast, it shows an increasing total irradiance with increasing solar activity from VIRGO data. MDI data have also revealed dramatic changes with the solar cycle of the large-scale, subsurface dynamics of the Sun [8], [9], [10].

**Sunquakes.** Sunquakes can provide new information about energy release and transport in solar flares. The first sunquake observed related to a flare in 1996 July 9. Circularly expanding waves on the solar surface were observed (Figure 2), the last X-class flare of the previous solar activity cycle and the first flare observed by SOHO. No sunquakes, however, were observed by SOHO until the X17 flare of 2003 October 28. This flare and two somewhat smaller flares, produce seismic waves observable with MDI. These new observations from SOHO provide unique information about the interaction of the high-energy particles associated with solar flares with the dynamics of the solar atmosphere during and after the impulsive phase of the flares, providing the new methods of helioseismologic analysis of flaring active regions, similar to that used in earthquakes study.

## 2.2 The Solar Atmosphere

Nagata et al. [11] found that hot loops visible in soft X-rays were distinct from the cooler loops visible in the EUV, and that, in general, the two types of loops alternated spatially. Neither of them seems to be isothermal.

Magnetic field as high as 1750 G at 6 Mm and 960 G at 12 Mm above a pair of large sunspots have been observed with MDI, CDS and EIT [12]. This means the first observation of plasma at temperatures as large as  $10^6$  K.

A database of over one hundred million EUV bright points has been assembled [16] from the approximately 360,000 EIT full-disk images over the last 12 years.

Marsh et al. (2003) [13] detected conversion from slow magnetoacoustic waves to kink waves, as a 5 minute oscillations were propagating from the chromosphere and transition region into coronal loops, being quickly damped.

### 2.3 Coronal Mass Ejections

An automated method to CME identification able to capture more than 75% of CMEs has been developed by Robbrecht and Berghmans [14].

SOHO UVCS, LASCO, and EIT have obtained a great amount of pictures and movies from CMEs (Figure 3), velocities have been measured. Very usefull CME catalogs have been provided to the scientific comunity, that permit an easier and better analysis and understanding of solar wind and solar energetic particle events. Studies about CME acceleration, coronal jets, current sheets, etc., have also been performed.

### 2.4 Solar Wind

SUMER observations are described in [15]. They account for solar wind acceleration in funnel-like flux tubes originated in coronal holes and establish the acceleration region between 5 and 20 Mm above solar surface.

McIntosh and Leamon (2005) [16], found solar wind velocities and composition from ACE in good agreement with the photospheric magnetic field measurements from MDI.

Vasquez et al. (2003) [17] and Cranmer and Van Ballegooijen (2005) [18] have studied the differences between fast and slow wind at solar minimum as an effect of the different rates of superradial flux-tube expansion over the polar coronal holes and at the edge of the streamer belt. A combination of the two effects is able to produce the observed differences: a raising of the height of the Parker critical point for flux tubes within about 20 degrees of the closed-field part of the streamer tends to produce a slow wind solution; and the near-streamer flux tubes undergo a lower rate of Alfvén wave dissipation at heights at and above the critical point, which leads to a lower wind speed and higher mass loss rate.

Observationally, there is growing evidence that coronal holes and streamers share at least some of the same microphysical processes.

UVCS observations have driven new interest in collisionless wave-particle resonances, specifically the ion cyclotron resonance, as potentially important mechanisms

for damping wave energy and preferentially energizing positive ions in the accelerating solar wind. But no observations are still made of ion cyclotron waves. There are several theories about the acceleration of ions in coronal holes but the topic remains without observational features that clearly determine which kind of instability may be working in the solar wind acceleration in coronal holes.

Related to solar wind composition the CELIAS MTOF group (at the University of Maryland) has recently identified a new type of event. In these Heavy Ion Depletion Events (HIDEs), He and all the heavier ions are depressed relative to solar wind protons by one to two orders of magnitude. Six of such events (with durations ranging from 6 to 48 hours) have been identified. At least three of these HIDEs occur in the declining phase of high speed streams.

## 2.5 Solar Energetic Particle

Energetic particles during quiet time periods detected by EPHIN have been analysed in [20]. Del Peral et al. [21] analysed the electron spectrum in the energy range 150 keV to 10 MeV, measured by EPHIN sensor on board SOHO observatory during 1996 quiet time periods. The results show that the dominant electron population is of jovian origin with spectral indexes in the range from 1.5 to 1.8. Estimation of the emission intensity of electrons from the jovian magnetosphere is also obtained. Unexpected recurrence of jovian electrons at the middle of 1996 during poor Earth-Jupiter magnetic connection has been observed (Figure 5).

Temporal profiles of energetic ions and electrons observed at 1 AU during solar energetic particle events are mainly determined by particle injection features, the observer location relative to the source region at the Sun, and the interplanetary space plasma and field conditions during particle transport. Gómez-Herrero et al. [19] analysis of the temporal profiles of 18 solar energetic particle events detected by EPHIN have been analyzed by fitting a pulse function to them in order to find a set of parameters which can be used to characterize the events. Composition and energy spectra of the different particle population are obtained for both impulsive and gradual SEP events [22].

The ionic charge distributions of solar energetic particles (SEP) events are an important diagnostic of the plasma and acceleration mechanisms and conditions at the source region in the solar corona. The large difference between gradual,  $Q(\text{Fe}) \sim 14$ , and impulsive,  $Q(\text{Fe}) \sim 20$ , SEP events has not yet been explained. New measurements of ionic charge states with instruments of improved sensitivity over a wide energy range on several spacecraft (SAMPEX, SOHO, ACE) have, however, shown that this picture was oversimplified. In gradual IP-shock related events, the ionic charge state of heavy ions was observed to generally increase with energy, with a large event to event variability. For impulsive events, previous work indicated a systematic but modest increase of  $Q(\text{Fe})$  with energy in the range 180-550 keV/nuc.

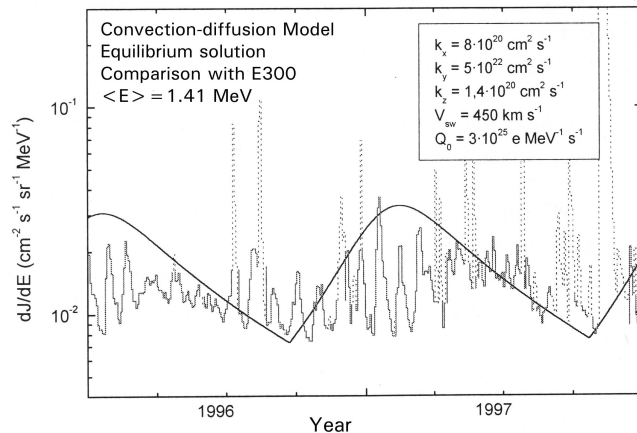


Figure 4: Differential electron flux values plotted in comparison with propagation model predictions (solid line). An unexpected jovian electron super-flux is observed beyond DOY 200 of 1996 during bad magnetic connection between Jupiter and Earth. Dotted lines correspond to SEP events.

However, measurements with SOHO CELIAS STOF now show that the ionic charge of Fe at energies  $\lesssim 100 \text{ keV/nuc}$  in these events is significantly smaller ( $\sim 12.5 \pm 0.9$ ). The large increase of the mean ionic charge of iron in the energy range  $\sim 10 - 550 \text{ keV/nuc}$  as observed with SOHO and ACE can be explained by the establishment of charge interchange during acceleration, as it has been stated by the ESCAPE model Rodríguez-Frías et al. [23], [24], [25] in the dense plasma environment in the low corona, as can be observed in Figure 6 for two impulsive solar events.

### 3 SOHO Scientific Objectives for 2010

The new ESA-NASA missions STEREO, Solar-B, Solar Dynamics Observatory (SDO), Solar Orbiter, etc., give a large number of new and enhanced opportunities. We can only enumerate briefly the future scientific objectives for SOHO in combination with the newer observatories data:

- Subsurface solar weather.
- Quadrature observations.
- Acceleration of the solar wind.

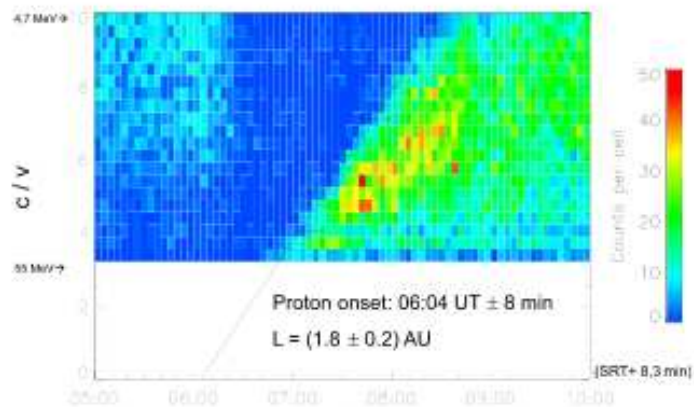


Figure 5:  $\beta-1$  vs time for EPHIN PHA protons during a solar energetic particle event onset.

- CMEs, current sheets, and shocks.
- Dependence of CME propagation on solar cycle phase.
- Reconstruction of CME morphology.
- Multipoint SEP sampling.
- Reconstruction of EUV loop morphology.
- Solar forcing of terrestrial climate.
- Operational information on CME speeds and directions.
- L1 solar wind monitoring under extreme conditions.
- Discovery science.

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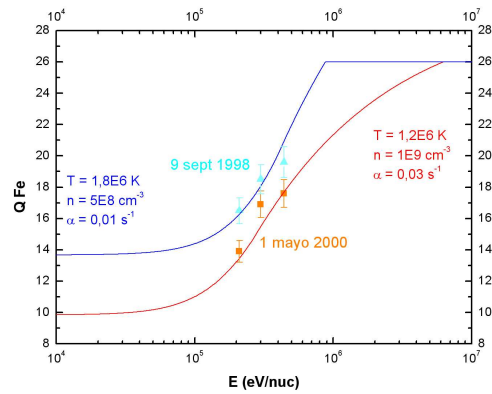


Figure 6: ESCAPE model prediction of the charge state dependence on the energy for two impulsive SEP events.

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