History of Physics (21)

SOHO – the ESA / NASA Solar and Heliospheric Observatory

I. Overview, a Window into the Solar Interior, and SOHO’s Instruments

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The Solar and Heliospheric Observatory SOHO is a space observatory that studies the Sun from its deep core to the outer corona and beyond – into the Heliosphere. SOHO is observing from a halo orbit around the first Lagrange point, L1, in the Sun-Earth system – about five light-seconds away from Earth toward the Sun (cf. Fig. 1). Launched in December 1995, SOHO is still operating today. Remarkably, it is the first joint ESA/NASA mission that is led by the European Space Agency.

From its vantage point at L1 SOHO observes the rich palette of solar phenomena depicted in Fig. 1. The internal structure of the Sun is shown in its cut out octant: fusion generates a temperature of about 15 MK in the core of the Sun; this energy-producing region extends to about the first quarter of the solar radius (0.25 R\textsubscript{9}). Heat then migrates through the radiation zone to about 0.75 R\textsubscript{9}, where convection sets in and becomes the dominant mode of energy transport to the 'surface'. The outermost atmospheric layer is the 300 km thick photosphere, which has a temperature of about 5800 K and radiates off most of the Sun's energy. A small part of the energy, in non-thermal form, is used to maintain the corona – an extended, tenuous atmosphere above the photosphere with a temperature reaching millions of kelvin –, and to accelerate the solar wind that sustains the Heliosphere.

The scientific goals of SOHO can be summarised by three questions, namely

- what are the structure and dynamics of the solar interior?
- why does the solar corona exist, and how is it heated to a temperature of millions of kelvin?
- where and how is the solar wind accelerated?

In this first part of an article on SOHO, we present an overview of the mission, address the first above question, and sketch SOHO's scientific payload. The still mysterious temperature increase above the relatively cool photosphere as well as the acceleration of solar wind will be the topic of the second part of this article in the next issue of the SPG Mitteilungen.

Helioseismology

At first sight, the aim implied by the first question above, namely looking into the solar interior to investigate its structure and dynamics, sounds rather extravagant. But exploring the solar interior did become feasible in 1975, after Deubner [1] had demonstrated that the five-minute oscillations, which had been discovered and extensively explored by Leighton, Noyes and Simon [2], are in fact a manifestation of global oscillations propagating throughout the Sun. This offered the prospect of probing the solar interior by helioseismology – a method analogous to geoseismology, where waves generated by an earthquake, for example, propagate inside the

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1 The Heliosphere is a bubble-like region in space that is dominated by the Sun. Plasma 'blown out' by the Sun – the solar wind – maintains this bubble against the outside pressure of the interstellar medium, i.e. the gas that permeates the Milky Way Galaxy (cf. https://en.wikipedia.org/wiki/Heliosphere).

2 This article is published under the rubric 'History of Physics', because it was originally expected that the SOHO mission would end this year. However, given the excellent current state of spacecraft and experiments and the prospective contributions of SOHO to NASA's recently launched Parker Solar Probe, an extension of the mission is now considered.

3 European industry built the SOHO spacecraft with ESA funding under ESA project management. NASA provided the launch by an Atlas II-AS rocket and ESA's Space Operations Centre (ESOC) in Darmstadt handled the navigation to L1. A joint ESA/NASA team, located at NASA's Goddard Space Flight Center (GSFC) in Greenbelt MD/USA, then took over the science operations, i.e. planning and verifying of the observing programme, while NASA controlled the spacecraft. The European experiments on SOHO have been designed, built and tested with national resources in laboratories of European Universities and research institutes. Across the Atlantic, the same applied to the NASA-provided instruments, except that they received their funding from NASA. Some instruments were actually the result of trans-Atlantic collaborations.
Earth and are measured as a time-dependent deformation of the surface. From such measurements on the surface of the Earth it is possible to gain information on the interior structure of the Globe. In the case of the Sun the oscillations are persistent. Their most easily detected form of appearance – the pressure modes – are standing acoustic waves. They manifest themselves in spherical harmonics. As an example, we show a single spherical harmonic in Fig. 2.

The frequency of such a mode depends on the course of the sound speed in the solar interior, and can be determined by observing the time-dependent deformation of the areas shown on the surface of the sphere in Fig. 2. On the Sun this can be done by observing either the periodic Doppler shift of a corresponding area on the photosphere 4, or by recording the periodic intensity changes of such areas that are associated with the oscillations. Since the local speed of sound in the solar interior depends on the progression of density and temperature with depth, an inversion procedure by use of a large number of modes and their frequencies is able to determine this course.

Such measurements are not trivial, however, since each radial order, \( n \), of the spherical harmonics appears with up to hundreds of angular degrees, \( \ell \), that have slightly different frequencies 5. The frequencies of the modes must be found from a Fourier analysis of the observed time series. At the frequencies observed for pressure modes (i.e., approximately 1 mHz to 5 mHz), this requires long, uninterrupted observing periods.

Early in the 1980s the first long, uninterrupted helioseismology observation was obtained during the southern summer by a telescope set up near the South Pole [4]. Later, networks of telescopes located around the globe have been set up to overcome the day-night cycle at fixed observing sites at low-lattitudes 6. As of early 1996 SOHO is also providing uninterrupted time series for helioseismology from L1 7.

Today, helioseismology is a wide, very active field. It uses observational and mathematical methods that are much more numerous and complex than what we can describe here: there is global and local helioseismology; and beyond the pressure modes discussed above, there exist gravity modes that are confined to the convectively stable interior of the Sun 8 as well as surface gravity modes. Moreover, helioseismology has spawned asteroseismology – seismology on stars 9.

The helioseismology payload of SOHO at L1 has produced several «Firsts» in solar physics. The use of the relevant instruments 10 has led to

- the first images ever taken of a star’s turbulent outer shell, i.e. of its convection zone,
- revealing the structure of sunspots below the solar ‘surface’ 11.

In addition, SOHO has

- provided the most detailed and precise measurements of
  - the internal temperature structure of the Sun (cf. Fig. 3),
  - the rotation of the solar interior, and
  - of gas flows in the solar interior.

Spacecraft and Science Payload

Fig. 4. shows the spacecraft with its twelve scientific instruments that enable the investigation of the palette of solar phenomena symbolised in Fig. 1. The scientific instruments are mounted on the upper part of the spacecraft, on the so-called payload module. A service module with equipment for power and communications, as well as propellants and thrusters for attitude and orbit control is located in the lower part of the spacecraft. The total mass of SOHO at launch was 1850 kg, its length along the Sun-pointing axis (its height in Fig. 4) is 4.3 m; the solar panels – the blue panels facing the technicians – are unfurled in space to a span of 9.5 m. Propellants, which were needed to guide SOHO from Earth to its halo orbit around L1 following the launch were part of the weight; the remainder of these propellants is now used to keep the spacecraft on its halo orbit, and to control the spacecraft’s attitude 12.

6 GONG (the Global Oscillation Network Group) and BiSON (Birmingham Solar Oscillations Network), set up by the US National Solar Observatory and by Birmingham University, respectively, are still operating today.

7 In 2010, NASA launched the Solar Dynamics Observatory (SDO) with an advanced helioseismology payload into an inclined geosynchronous orbit, where the spacecraft is also in permanent sunlight.

8 Refer to Fig. 1 for the internal structure of the Sun.

9 A general, albeit very concise description, of the principles and the history of helioseismology (and asteroseismology) is available in the Wikipedia article: https://en.wikipedia.org/wiki/Helioseismology#Global_helioseismology.

10 SOHO’s instruments used for helioseismology observations are described, in the context of the entire scientific payload below.

11 Note that both these accomplishments have used the method of local helioseismology.

12 The halo orbit around L1 is not gravitationally bound; SOHO therefore needs propellants to follow its trajectory. A halo orbit, rather than station at L1 was chosen, because it uses less propellant than keeping the spacecraft in the metastable Lagrange point. See from Earth, SOHO’s orbit keeps
SOHO’s Science Payload consists of three parts: the Helioseismology Experiments, which take full advantage of the continuous sunlight at L1 to record the long time series needed for high-resolution Fourier transforms; the imaging helioseismology instruments also take advantage of the spacecraft’s stabilisation to one arc second, the Solar Wind and Particle Payload, which benefits from the fact that L1 is far away from the Earth’s magnetosphere and offers full access to the solar wind, and the Coronal Payload, which is used to investigate the solar phenomena depicted in Fig. 1 with high spatial and spectral resolution over a wavelength range extending from the visible to X-rays. In addition, three coronagraphs with fields of view extending to 30 R_☉ permit observations of the lively extended corona – and have led to unexpected discoveries of numerous comets.

The three helioseismology experiments and the institutions of their Principal Investigators are

- MDI/SOI – the Michelson Doppler Imager/Solar Oscillations Investigation, Stanford University CA/USA,
- GOLF – Global Oscillations at Low Frequencies, Institut d’Astronomie Spatiale, Orsay/F and
- VIRGO – Variability of Solar Irradiance and Gravity Oscillations, Physikalisch-Meteorologisches Observatorium Davos/CH.

They provide measurements of both intensity and Doppler-shift oscillations with spatial resolutions ranging from very high to modest, i.e. from 10⁶ to a few data points or even to a single element, namely the solar disk. This, together with the wide frequency range covered, yields a comprehensive insight into the structure and dynamics of the solar interior (cf. Fig. 3). Measurements of the line-of-sight component of the magnetic field are also provided; and accurate measurements are taken to quantify the variability of the total solar irradiance (still paradoxically known as ‘solar constant’) over periods of days to the duration of the SOHO mission.

The four instruments of the solar-wind and particle payload and their PI institutions are:

- CELIAS – the Charge, Element and Isotope Analysis System, Max-Planck-Institut für Extraterrestrische Physik, Garching/D
- COSTEP – the Comprehensive Suprathermal and Energetic Particle Analyzer, University of Kiel/D
- ERNE – the Energetic and Relativistic Nuclei and Electron experiment, University of Turku/FIN and
- SWAN – Solar Wind Anisotropies, Service d’Aéronomie du CNRS, Verrières-le-Buisson/F

These experiments continuously sample the solar wind as well as more energetic ions that are not only of solar, but also of interplanetary and interstellar origin. The latter measurements permit a classification of the wide range of energetic particle populations of solar, interplanetary and galactic origin. The SWAN experiment – the only instrument on SOHO that doesn’t look at the Sun – studies the interaction between the solar wind and hydrogen atoms from interstellar space that intrude into the Solar System. SWAN thus determines how the solar wind is distributed within the Heliosphere.

The five experiments of the coronal payload and their PI institutions are:

- EIT – the Extreme ultraviolet Imaging Telescope, Institut d’Astronomie Spatiale, Orsay/F

The spacecraft about 45° off the Sun. The antennas of the NASA Deep Space Network thus receive the pure data stream, free of a background of solar radio emissions.
CDS – the Coronal Diagnostics Spectrometer, Rutherford Appleton Laboratory, Chilton/UK
SUMER – Solar Ultraviolet Measurement of Emitted Radiation, Max-Planck-Institut für Sonnensystemforschung, Göttingen/D
LASCO – the Large Angle and Spectrometric Coronagraph, Naval Research Laboratory, Washington DC/USA and
UVCS – the UltraViolet Coronagraph Spectrometer, Smithsonian Astrophysical Observatory, Cambridge MA/USA

EIT, the ‘eyes’ of SOHO, provides full-disk images of the Sun in the extreme ultraviolet that map the plasma in the low corona at temperatures between 80 K and 2.5 MK. The two imaging spectrometers CDS and SUMER provide diagnostics of solar plasma, and enable the determination of the temperature and density, as well as of flows of the solar plasma over a temperature range from 10 K to 2 MK. LASCO creates a permanent artificial solar eclipse that reveals the solar corona from near the limb to a distance of 30 R\(_s\), or ca. 21 Gm, i.e. about a seventh of the distance between the Sun and the Earth; LASCO unexpectedly turned out to be a fertile comet finder (see info box). UVCS also creates an artificial eclipse with a field of view ranging from 1.3 to 12 solar radii and permits analysing the microscopic and macroscopic behaviour by observing the less intense far-ultraviolet emission of the highly ionised plasma in the corona.

Planning the Observing Programme

Parts of the science payload are complementary, as demonstrated by Fig. 2, which is based on data obtained by both the MDI/ISOI and the VIRGO instruments. The complementarity of experiments helped significantly in addressing the complex solar processes under investigation. But this required a close coordination of SOHO's observing programme. For several years after launch, representatives of the groups that had contributed payload instruments, were present at the Science Operations Centre (located at the Goddard Space Flight Center, GSFC, in Greenbelt MD/USA) to jointly develop, and agree on the daily – and longer-term – observing programmes. Observing planning also was guided by daily data on solar activity provided by ground-based solar observatories; in turn SOHO also performed space observations that were coordinated with observatories located around the globe.

Preview: Part II addressing SOHO's findings in coronal and solar wind physics will appear in the next issue of the SPG Mitteilungen. We will also discuss the challenges of radiometric stability, particularly of instruments designed for observing extreme-ultraviolet radiation and the stringent cleanliness requirements to be applied to all work on the ground. We will also mention the accidental loss of the spacecraft in June of 1998 and particularly its successful recommissioning of all the instruments by November of that year.

References

SOHO the Comet Finder

SOHO – conceived as a solar flagship mission – turned out to be a very productive comet finder as well. Over 3000 such objects passed through the wide field of view of the Large Angle and Spectrometric Coronagraph LASCO. Most of these objects were unknown ‘Sun-grazing’ comets; some of them survived their perihelion, but others burned up during a fiery encounter with our daystar.

Comet 2012/S1 (ISON, cf. Fig. 5) was a peculiar case. After its discovery in the autumn of 2012 its perihelion was predicted for November 28, 2013 with a distance of only 1.2 Gm (or ca. 1.7 R\(_s\), above the solar surface). Early on ISON was rather bright and some astronomers hoped that it might become a "comet of the century" after perihelion – “a stunning celestial phenomenon” in the weeks preceding Christmas 2013. But as the comet appeared in LASCO’s field of view, its tail became increasingly faint. A detailed analysis of the encounter that also included observations by SUMER showed that the comet broke up or disintegrated shortly before its perihelion.

1 The movie https://soho.nascom.nasa.gov/hotshots/2015_09_15/G2015-069_3000SOHOcometsV2-H264_Good_1080_29.97.mov shows the trajectories and describes the categories of the comets observed by LASCO.
2 An in-depth data analysis, which also made use of SUMER observations, has revealed that comet 2012/S1 (ISON) stopped producing dust and gas shortly before it raced past the Sun and disintegrated (cf. http://sci.esa.int/soho/54344-comet-ison-dramatic-final-hours/.

Figure 5: Observations by the wide-angle LASCO coronagraph on SOHO. The small white circle indicates the size and location of the solar disk, whose bright radiation is blocked by an occulting system mounted on the beam sticking into the image. (The bright star to the lower left is the red supergiant Antares.) This composite, spanning three days, shows how the comet had entered the field of view of LASCO on the lower right, brightened dramatically, but gradually evaporated after perihelion. A movie of the encounter with further details is found on http://sci.esa.int/science-e-media/video/44a/496_SOHO_LASCO_comet_ISON_27-30Nov2013.mov.