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In part I of this article \(^1\) we introduced SOHO, a spacecraft observing the Sun from L1, the first Lagrange point of the Sun-Earth system, since March 1996, and discussed the first of the three grand goals of the SOHO mission, namely ‘exploring the structure and dynamics of the solar interior’. This is done by the method of helioseismology, which relies on measuring solar oscillations. SOHO’s data resulted in the most detailed and precise measurements of temperature, rotation, and gas flows in the solar interior.

The first part further contained a description of the spacecraft and the twelve, partially complementary instruments that form SOHO’s science payload. These instruments – provided by consortia of investigators in Universities and Research Organisations both in Europe and the U.S. – are being deployed to study the Sun from space in a jointly agreed observing programme, whose data are accessible from the SOHO Archive \(^2\).

The present second part of the article addresses the two other grand scientific goals of SOHO, namely

• ‘why the solar corona exists and how it is heated to a temperature of millions of kelvin’, and
• ‘where and how the solar wind is accelerated’.

Mission Status

It is expected that SOHO operations will eventually be extended for a period of six years from now, to support NASA’s ‘Parker Solar Probe’ \(^3\). This mission, launched in August 2018, already had a first close fly-by at the Sun. SOHO’s Large Angle and Spectrometric Coronagraph LASCO, in particular, will take images of the solar corona over a field of view extending to 30 solar radii, while the Parker Solar Probe will go through four annual perihelia and probe the corona \textit{in-situ}. At the last perihelia scheduled for 2024 and 2025 the Parker Solar Probe will approach the Sun within a distance of ca. 9.5 solar radii above the photosphere, its perceived ‘surface’!

Some of SOHO’s instruments are still observing regularly; others, which had been turned off earlier in the mission, were turned on occasionally for specific observing campaigns (such as the observations of the perihelion of Comet ISON in December 2012) \(^4\).

The performance of the SOHO spacecraft and its instruments over the now nearly 23 years of observations has been perfect – except for the dramatic, but fortunately only temporary loss of contact in June 1998 (cf. box III).

I. The Discovery of the million-kelvin Temperature of the Solar Corona in 1942

Total solar eclipses have startled humans for millennia wherever they occurred. After astronomers were able to predict the place and time of a total eclipse, the scare among the general population began to fade. For astronomers the enigma of the ‘corona’ (‘Strahlenkranz’) surrounding the occulted solar disk remained. After the view that the corona was part of the Sun (rather than an optical artefact) had taken hold early in the 18\textsuperscript{th} century, a new riddle appeared as of 1869, when spectral lines observed in the corona during total solar eclipses could not be assigned to any known chemical element!

In 1942 the Swedish physicist Bengt Edlén showed conclusively that the wavelengths of these ‘unknown’ lines actually corresponded to forbidden transitions between levels of the ground configurations of highly ionised atoms – mainly of iron, nickel and calcium. From the ionisation stages in question Edlén established that coronal temperatures must be of order \(10^6\) K [1-3].

Exploring the Corona and the Solar Wind

As described in box I the mystery of a corona surrounding the Sun was lifted only in 1942 after Bengt Edlén had shown that the emission lines observed in the corona were produced by highly ionised ions, and that the corona’s temperature therefore was of order \(10^6\) K.

The existence of a million-degree plasma above the much cooler photosphere presents a riddle though: what is heating the corona? Normally, one would expect a steadily decreasing temperature of any plasma or gas residing above the photosphere. But given the high temperature of the corona one must assume that non-thermal energy is somehow transported to, and deposited at greater height, where it is converted into heat that is carried away by radiation and by thermal conduction to the cooler, lower-lying parts of the atmosphere, or is used to accelerate the solar wind.

In box II we summarise how the temperature and density structure of the plasma in the outer solar atmosphere is derived from its extreme-ultraviolet spectrum. This spectrum contains emission lines of many ionisation stages of the more abundant chemical elements. With increasing height higher ionisation stages of a given element are present.

The solar atmosphere lying above the photosphere is traditionally subdivided into three regions, namely the ‘chromosphere’, ‘transition region’ and ‘corona’. An average course of temperature and density in atmospheric layers starting at temperatures occurring within, and then above the photosphere is shown in Fig. 3a of box II.

1 See SPG Mitteilungen Nr. 56:34-37 (2018)
2 http://sci.esa.int/soho/45900-esa-s-new-soho-science-archive-now-online/
3 https://en.wikipedia.org/wiki/Parker_Solar_Probe
4 cf. ‘SOHO the Comet Finder’ at the end of the first part of this article [SPG Mitteilungen Nr. 56:34-37 (2018)].
Because the solar atmosphere is inhomogeneous plasma, a proper investigation of the outer solar atmosphere requires observations not only of the spectrum, but also of so-called spectroheliograms, i.e. monochromatic images of the atmosphere – and this over an extended time. Furthermore, as the outer atmosphere shows a rather dynamic behaviour (and sometimes – such as by flaring – even exhibits violent events) a movie-like coverage is of importance as well. Stabilised space platforms that made such observations possible became available in the 1960s.

A definitive verdict about the processes that heat the corona and accelerate of the solar wind – the two remaining grand scientific goals of SOHO – cannot be rendered yet. Rather than now presenting a tedious list of plasma processes that have been shown to potentially contribute to heating the corona and/or accelerate the solar wind, we prefer to illustrate now how satellite platforms in space have helped to make progress in investigating a prominent coronal phenomenon, namely coronal holes.

Coronal holes have been in the focus of solar space research for decades. From correlating observations of coronal holes on the solar disk and successive solar-wind observations near the Earth, it had been inferred that coronal holes might be the source of fast solar wind streams – a supposition that later was confirmed (cf. Fig. 8).

Magnetic field lines coming out of a coronal hole are open, in contrast to magnetic field lines above the adjacent quiet corona, which are generally closed (cf. Fig. 4). As a consequence, it turns out that the shape and position of the temperature curve of the ‘quiet’ atmosphere shown in Fig. 3b is modified inside a coronal hole.

The Story of Coronal Holes – Progress in the Course of three Space Missions

Our understanding of the properties of coronal holes has benefitted from increasingly sophisticated observing techniques employed by use of three major solar space observatories, namely the two NASA missions OSO-6 and Apollo Telescope Mount (ATM) on Skylab, as well as the joint ESA/NASA SOHO. The scientists involved have also changed their behaviour – along with the technical advances: they introduced joint observing planning and increased the collaboration between the instrument teams along with instituting a policy of open data access that eventually led to freely accessible archives containing the collected calibrated data.

1. OSO-6 – the sixth Orbiting Solar Observatory

The OSO-6 satellite, launched in August 1969 and shown in Fig. 1, contained two pointed instruments, one of which was the spectroheliometer to be discussed here. A spectroheliometer is a telescope-spectrometer combination for solar observations that is equipped with a photoelectric detector. In the telescope’s focus there is a spectrometer ‘slit’. In the instrument in question this ‘slit’ was a 35° x 35° aperture, and the spectrometer was able to scan a wavelength range between 28.5 nm and 138.5 nm, chosen to study the solar chromosphere, transition region and corona.

The two basic modes of a spectroheliometer are, (i), generating a monochromatic image by scanning the telescope axis over the Sun with the spectrometer set to a fixed wavelength and, (ii), recording the spectrum of a specific point on the Sun by obtaining a wave-length scan with a fixed telescope pointing. The OSO-6 satellite provided the articulation of the telescope axis for both these modes: based on commands from the ground it pointed the telescope axis to any position within a 45′ x 45′ field of view (FOV) centred on the Sun, or it performed a raster scan over any desired area within the FOV.

5 We recall that the first solar spectra photographed above the ozone layer by a spectrograph mounted on a rocket were obtained in 1946. Hard work over more than a decade then was needed to develop stabilised satellite platforms with tape recorders that could perform the required measurements.

6 ... often jokingly referred to as the second-most interesting kind of hole in astronomy.

7 OSO-6 was in a near-circular orbit at 530 km altitude with a 90-min period and 33° inclination. During its orbit the satellite was in daylight for 60 min and spent the remaining 30 min behind the Earth.

8 ...OSO’s pointing system performed the raster scan mechanically in a boustrophedonic pattern (so named after oxen plowing a field): there is a turn after each ‘line’ in the pattern, and no retrace to the beginning of the next line, as ‘raster’ usually implies.

9 In its ‘wheel’ OSO-6 also carried instruments that saw the Sun every 2 s. Some of these instruments observed the Sun, others had been designed to observe non-solar objects in the sky. A slow roll of the spacecraft about the line of sight to the Sun provided the instruments in the wheel with access to the entire celestial sphere over six months.

10 The choice is suitable, but not impartial; the author participated in preparing and calibrating instruments that obtained the observations to be discussed; the first two while working at Harvard College Observatory in Cambridge MA/USA, the third one after he had returned to Europe to work at ETHZ and ESA.

11 Note that these three space observatories easily cover half a century, if one includes the time for pre-launch preparations, operation, and data interpretation. A change in social behaviour may therefore be expected.

12 The symbols ′ and ″ are used for arc minute and arc second, respectively.

13 As the solar disk has a diameter of ca. 32′, the field of view extended well into the corona.
II. From the EUV-Spectrum of the Sun to the Structure of Its Outer Atmosphere.

The extreme-ultraviolet (EUV) spectrum of the Sun (Fig. 2) is an emission spectrum – quite in contrast to the visible solar spectrum that we know from textbooks, where a colourful stretch of continuum radiation is interspersed with dark Fraunhofer lines (which indicate the presence of a given element in the Sun, and can be used to determine the solar abundance of the chemical elements).

Fig. 2 — The outer solar atmosphere reveals its structure through the extreme-ultraviolet (EUV) spectrum. This spectrum, recorded by the SUMER instrument on SOHO, contains mainly emission lines 14. The spectral resolution of SUMER also provides information on line profiles and Doppler shifts; its information content thus exceeds by far what can be shown in this reproduction 15. From [7].

Starting from this spectrum one can determine the temperature and density structure of the outer solar atmosphere. The strength of a given emission line in Fig. 2 depends on the abundance of the element in question 16, on the calculated fractional ionisation equilibrium of the ion to which the emission line in question belongs, on atomic parameters as well as on the temperature and density structure of the outer solar atmosphere. In turn, the course of the latter parameters can iteratively be determined from the apparent strengths of the lines observed, provided the spectrum has been obtained by a radiometrically 17 calibrated spectroheliometer like SUMER.

The plot of Fig. 3a renders the course of temperature and density in the outer solar atmosphere – within its subdivisions: chromosphere, transition region and corona.

14 Labels identifying the emission lines follow the spectroscopic notation, where the roman numerals indicate the spectrum to which the lines belong. The first spectrum is that of the neutral atom; a line belonging to the second spectrum, such as N II, accordingly is emitted by singly ionised N\textsuperscript{+1}.

15 On this reproduction a spectral resolution element corresponds to 5 µm.

16 ...which, to start with, is assumed to be the same as that derived from visible spectra of the photosphere.

17 Rather than ‘photometric’, whose definition is related to human vision, we prefer ‘radiometric’, which relates to measurements of electromagnetic radiation at all wavelengths.

Fig. 3 — a) Top: Temperature, T, and density, \( \rho \), vs height in the outer solar atmosphere (from [8]). b) Bottom: a temperature profile labelled with some ranges of EUV line formation; by the choice of an ion, whose spectral lines one observes, one simultaneously selects the height of the atmospheric feature to be observed (if one assumes a homogeneous plasma). From [9].

Fig. 3b shows the part of the \( T \) vs. \( h \) model starting at the foot of the transition region that is particularly relevant for deriving the atmospheric structure based on the spectrum of Fig. 2. Temperature (and height) range where a given ion contributes to the radiative output is marked. This presentation assumes a homogeneous atmosphere – a useful initial assumption that is however not realistic. The reason is that the plasma \( \beta \) (i.e. the ratio between plasma and magnetic pressure) is very small in the tenuous plasma of the outer solar atmosphere; the magnetic field therefore strongly determines the geometry of the plasma (cf. Fig. 4).

Fig. 4 — Schematic magnetic field lines that could fit the borders of a coronal hole. (Note: to match the orientation of the polar coronal hole in Fig. 7 the picture has been rotated by 90°.)
The spectroheliometer on OSO-6 had only one detector – an open magnetic electron multiplier (MEM) with a tungsten cathode \(^\text{18}\), where the photoelectron and the secondary electrons were multiplied on a continuous dynode strip. Crossed magnetic and electric fields forced electrons released after each impact back to the dynode strip and carried them along towards the anode, where the arriving electron avalanche triggered a counter \(^\text{10}\).

A remarkable aspect of the OSO-6 experiment was its ‘quick-look’ system. Observing at short wavelengths often requires a reaction to changing conditions on the Sun. With OSO-6 it was possible to receive formatted data of the observations in real time (or from a playback of the tape recorder) as long as the satellite was within view of a NASA ground station. The ‘quick-look’ system transmitted data received at the ground station to the Goddard Space Flight Center in Greenbelt MD for data processing and then via a dedicated phone line to a line printer \(^\text{19}\) at Harvard College Observatory (HCO) in Cambridge MA. Instrument settings could then be changed in response to a new situation, if necessary.

In order to draw quantitative conclusions from the EUV radiation received, the instrument’s absolute responsivity had been determined in the laboratory before launch; but it was soon noted that the (absolute and wavelength-dependent) responsivity changed in space.

After eight months, when the loss had reached a factor of twenty it was decided to cease observing with OSO-6. The drop of responsivity was probably caused by a combination of loss of the reflectivity of the telescope mirror and loss of detector efficiency – both the consequence of molecular contamination \(^\text{21}\).

The OSO-6 spectroheliometer in Fig. 5 shows a coronal hole.

2. The Apollo Telescope Mount (ATM) on Skylab

Skylab (shown in Fig. 6) was a space station built with hardware left over from the Apollo Moon missions, and was launched by a Saturn-V rocket in May 1973. Three crews, each composed of three astronauts, were launched in Apol-

\(^\text{18}\) A tungsten cathode is insensitive to any remaining stray-light caused by the overwhelming visible and near-ultraviolet photospheric radiation, because its work function exceeds by far the energy of photons at the wavelengths in question. Such cathodes are called ‘solar-blind’.

\(^\text{19}\) Spectroheliograms could be visualised on a line printer by making use of print characters with different amounts of ink and by overprinting lines.

\(^\text{20}\) An early kind of fax machine.

\(^\text{21}\) Assembling and testing of the spectroheliometer for the OSO-6 mission as well as launch preparations took place in cleanrooms, of course. However, the cleanliness specifications at that time were numerically defined only for particulate contamination. Later it was realised that molecular contamination of optical elements can lead to polymerisation and subsequent loss of reflectivity upon exposure to extreme ultraviolet radiation in space. For the later SOHO mission the builders of the spacecraft used a cleanliness requirement of a few hundred ng/cm\(^2\) of condensable and particulate contamination, and the instrument teams aimed for even less. A more stable responsivity in orbit was achieved in this way (cf. \([\text{13}]\)).
lo Command and Service Modules (CSM) on Saturn-IB rockets to visit Skylab, where they docked their CSMs. At the end of their visits they entered into the CSM and used it for their return to Earth. The first crew spent a month on Skylab, the second and third crews two and three months, respectively.

All the solar telescopes in the ATM had internal pointing capabilities, and most used photographic film. Only the Harvard spectrophotometer had photoelectric detectors. Use of film was possible on Skylab: the astronauts brought the exposed film back to Earth for developing and subsequent use in research. A definite advantage was that the astronaut observing the Sun could immediately respond to unexpected events occurring on the Sun.

Fig. 7 shows Skylab observations of a coronal hole on the solar limb. We deduce that the temperature gradient within the coronal hole is less steep than in what usually is called the ‘quiet’ outer solar atmosphere. Note also that both the spatial resolution of Skylab observations (pixel-size: 5” x 5”) and the visualization have improved as compared to the OSO-6 spectroheliogram shown in figure 5.

Fig. 7 — An example of Skylab observations. In panel a) a plot of the height of the limb over the south pole of the Sun, as seen in the Ne VII line at $\lambda = 62.5 \text{ nm}$ (whose temperature of formation is $T_r \approx 7 \times 10^6 \text{ K}$) beyond the limb formed by the radiation of the Lyman continuum (with $T_r \approx 10^6 \text{ K}$). From the separation of the apparent limbs corresponding to the two temperature indicators Ne VII and Lyman continuum, one concludes that the temperature gradient inside a coronal hole is more gradual than that observed outside coronal holes: the strong rise of temperature shown in Fig. 3b of Box II is more gentle inside a coronal hole and owing to the absence of radiation of Mg X (as evident from panel b) the temperature reaches a plateau below $T_r \approx 10^6 \text{ K}$. Panel b) is a representation of a set of spectroheliograms photo-electrically recorded in the Mg X $\lambda = 62.5 \text{ nm}$ line ($T_r \approx 10^6 \text{ K}$) that show the extent of the coronal hole near the pole. (From [14]).

3. SOHO Observation of the Solar-Wind Speed in an Area Covered by a coronal Hole

The SUMER instrument on SOHO used imaging photon counters – a major advantage over the OSO-6 and Skylab instruments that had only, respectively, one and seven photon counters. With its considerably improved spatial resolution of ca. 1" and a spectral resolution that permitted measuring Doppler shifts 22. SUMER thus could observe Dopplergrams that cover an extended field of view and, as seen in Fig. 8, confirm that coronal holes indeed act as a source of fast-solar-wind streams.

Fig. 8 — Coronal holes are source regions of fast solar wind. Spectral lines observed in an area covered by a coronal hole exhibit a blueshift, while redshifts prevail in the surrounding quiet solar atmosphere. Dark borders marked on the Dopplergram are boundaries of so-called magnetic network cells. This phenomenon, which was known from EUV observations by ATM, shows the influence of the magnetic field on a smaller scale than with the overall boundary of a coronal hole. ATM observations had also shown that the boundary of a coronal hole coincides at low altitude with boundaries of network cells. Background: solar image taken by SOHO’s Extreme Ultraviolet Telescope (EIT) around $\lambda = 19.5 \text{ nm}$, representing solar plasma at $T \approx 1.6 \text{ MK}$. (From [15]).

Dynamic Events in the Corona: Mass Ejections that Propagate into the Heliosphere

SOHO also provided much information on the dynamics of the upper solar atmosphere. This may best be illustrated by movies taken by the Large Angle Solar Coronagraph (LASCO) instrument on SOHO. Coronal Mass Ejections (CME) had already been regularly studied by use of photographs taken by the coronagraph flown on board of Skylab, but the improved image quality and the wide field out to 30 solar radii, as well as the faster image cadence recorded by the charge-coupled devices (CCD) on SOHO’s LASCO, keep extending our knowledge about these energetic events that disturb the heliosphere 23.

A coronal transient traveling directly toward the Earth will perturb the terrestrial plasma environment, and influence what has become known as ‘space weather’. In the worst case satellite failures might result, and power surges in installations on the ground could occur. SOHO thus also helps to forecast the space weather in the Earth’s environment.

Conclusion

As the jury is still out regarding a definitive judgment on the panoply of candidate processes envisaged for heating the corona and/or accelerating the solar wind, we preferred to demonstrate how our knowledge of a specific topic, namely ‘coronal holes and the fast solar wind stemming from them’ has increased by use of advanced instrumentation. Studies of coronal heating will require observations with even higher spatial, spectral and time resolution than those available on SOHO [16].

22. Note the remark in the caption of Fig. 2 of box II: “The spectral resolution of SUMER also provides information on line profiles and Doppler shifts …”

III. «Lost in Space» – SOHO’s Recovery and then the first Gyro-less 3-Axis Stabilised Spacecraft!

“The SOHO mission almost ended on 25 June 1998 when control was lost during a routine spacecraft manoeuvre.” and “The science scientist’s and space engineer’s worst nightmare was beginning to unfold – SOHO was lost in space!” – detailed reports about this event [17, 18] start with such gloomy sentences. Indeed, after loss of contact the spacecraft was spinning, lost electrical power and was no longer pointing at the Sun. ESA experts immediately travelled to the US to support the local operations personnel at the SOHO Operations Center in Greenbelt MD.

On 23 July researchers from the US National Astronomy and Ionosphere Center (NAIC) offered to employ bi-static radar, with the 305-meter diameter dish of the Arecibo radio telescope in Puerto Rico transmitting radar pulses towards SOHO and the 70-m dish of NASA’s Deep Space Network in Goldstone (CA/USA) receiving the echo. On the next day, the spacecraft was located! The radar echoes confirmed SOHO’s predicted location and revealed a spin rate of about 1 rpm.

A carrier signal from SOHO was then detected on August 3. This meant that the spacecraft’s battery was being charged again; and when telemetry was received on August 8 the recovery of SOHO could commence. The first tasks now were to allocate the limited electrical power available and to determine SOHO’s anomalous orientation in space. On August 12, the thermal control heaters of SOHO could be switched on in order to start the thawing of the frozen hydrazine fuel tank; thawing pipes and thrusters then followed. Now SOHO could be re-oriented towards the Sun. Further recovery activities concerning the spacecraft-bus then took place and after an orbital correction manoeuvre on September 25, the SOHO spacecraft was in its normal mode again.

Recovery of the instruments took place between October 5 and 24, 1998. All instruments could be re-commissioned, although they had seen temperature extremes from below -120 °C to +100 °C. Some instruments were found to have an improved performance – contamination on mirrors and detectors had apparently evaporated during the hot periods.

SOHO was back in service now, but further trouble was still in store: two of the three gyro units that could provide attitude control had not survived the period when SOHO was out of control. The third gyro did fail on December 21. Attitude could still be maintained by manual thruster firings, but this procedure consumed fuel at a rate of 7 kg per week. ESA therefore accelerated the development of software for a new gyro-less operation that had been started when the failure of the other two gyros was known. And on February 1, 1999, after the new software was installed, SOHO became the first 3-axis stabilised spacecraft without gyroscopes!

ESA is currently preparing the Solar Orbiter mission for launch in 2020. Its spacecraft will explore the inner heliosphere by following a trajectory bringing it within only 0.3 AU from the Sun, and eventually up to solar latitudes around 25°. The latter will facilitate investigations of the atmosphere near the pole of the Sun.

The Solar Orbiter payload combines remote sensing with \textit{in-situ} analysis of the environment. The mission’s overarching goal is to find an answer to the question: How does the Sun create and control the heliosphere?

References


