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Solar Missions - getting closer to our Star

Editorial

The origin of space-based solar astrophysics goes back to the 1930s (Regener/Regener 1934) and early post-war years in the second half of the 1940s. German V2 rockets and so-called sounding rockets enabled to reach very high altitudes at the edge to space which was unreachable by balloons launched already decades before and at the time for exploring the upper atmosphere. Equipped with dedicated instruments, sounding rockets were able not only to measure geophysical or geomagnetic parameters, but solar radiation and particularly the solar spectrum beyond the visual regime. One of the most prominent scientists developing and using this new technique of sounding rockets was Homer E. Newell (1915 to 1983), who later became influential in NASA's administration. It is largely thanks to him that modern space-based astrophysics, and solar physics in particular, has undergone such a rapid and successful development (Newell 1980, Ruley 2012). The first measurements and observations outside the Earth's atmosphere were not only of the Earth's gravitational field and the Earth's magnetic field, but above all of solar wind, cosmic radiation and the solar spectrum (Berkner/Odishaw 1961, Liller 1961). Pioneering work was also carried out by James Van Allen (1914 to 2006) with the discovery of the radiation belt named after him. Even before the first concepts for an artificial Earth satellite were fully developed and technically feasible, instruments for observing the Sun and cosmic radiation were developed as early as in the 1930s to the mid-1950s for installation in sounding rockets, small satellites and space probes (Van Allen 1956, Corliss 1965). A detailed history of space exploration including the development of solar research from space is given in the outstanding two-volume monography published by ISSI (Bleeker/Geiss/Huber 2001).

Because of this long history of space-based solar astrophysics, it is worthwhile to get an overview of the development of satellite missions of the past few decades that serve to observe the Sun and the heliosphere. Dr. Anuschka Pauluhn from the Paul Scherrer Institute has taken on this task especially for the publication of this issue of *Spatium*. She has been responsible for the cross-calibration of several EUV instruments on the Solar and Heliospheric Observatory, SOHO. Later she worked on the analysis of solar EUV time series and simulation of flaring events in order to estimate the impact of nanoflaring events on the heating of the solar corona. She acts as a member of the pro ISSI association, which is part of the public outreach team of the International Space Science Institute ISSI in Bern.

Andreas Verdun
Zimmerwald, November 2023

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Cover
Artistic impression of Solar Orbiter (left) and Parker Solar Probe (right). It is neither to scale nor does it depict a realistic configuration of the two missions. (Credit: Solar Orbiter: ESA/ATG medialab; Parker Solar Probe: NASA/Johns Hopkins APL).

Solar Missions – getting closer to our Star

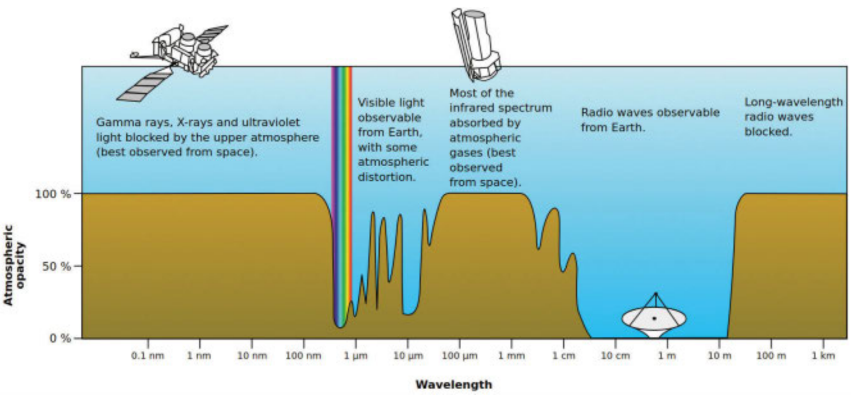
Anuschka Pauluhn, Paul Scherrer Institut, Villigen

1. Historic Observations / Early Missions

Observations of the Sun are as old as mankind. As the source of energy for planet Earth it has been of paramount interest since ancient times. However, although with increasing number and improved quality of observations, the description and understanding of various phenomena advanced, the mysteries, like for example the dark spots appearing on its surface, did not vanish. Instead, new puzzles and questions appeared, like how can the high temperatures in the outer solar atmosphere be maintained? For a general introduction the two *Spatium* issues by E. Parker (No. 22, 2008) and K. Schrijver (No. 44, 2019) are recommended, as well as the *Spatium* by R. von Steiger (No. 2, 1998), the latter in German. *Spatium* No. 17 by A. Balogh (2006) presents an introduction to heliospheric research. The issue No. 8 by J. Beer (2001) investigates the solar influence on the terrestrial climate and how to separate solar from man-made climate changes. As it became known that humanity is increasingly dependent on the varying conditions within the heliosphere, the so-called space weather, defined by the solar wind and interplanetary magnetic field, the interest in solar research grew further. Powerful events in the solar corona, known as coronal mass ejections, or CMEs, can propel billions of tonnes of energetic particles out into space at millions of kilometres per hour. If Earth lies in the path of a CME, the latter can trigger a major geomagnetic storm, in which satellites may be damaged, telecommunications disrupted, astronauts endangered and power grids subjected to dangerous surges in electrical currents.

Ground-based telescopes, however, limited to observations in the spectral part that is not blocked by the terrestrial atmosphere, have made significant contributions to the current knowledge. They are usually located at sites where perturbations by seeing effects (i. e., the smearing of the images by varying light paths through the atmosphere) are minimal and can be further optimised. One of the first modern solar telescopes (of an aperture of 61 cm) was set up by George Ellery Hale at Mount Wilson near Pasadena, California, in 1904. It is still in operation, mainly for education and public outreach now. The largest solar telescope today is the DKIST (Daniel K. Inouye Solar Telescope) on Maui, with an aperture of 4 m in diameter. The largest solar telescope in Europe with an aperture around 1.5 m is the GREGOR instrument on Tenerife, Spain. Ground-based solar telescopes can also measure in the radio wavelength, or host detectors for neutrino measurements and the search for exotic particles from the Sun, such as axions[1].

Figure 1: Percentage transmission of radiation through the Earth's atmosphere. (Source: ESA/NASA, Public domain, via Wikimedia Commons).



[1] Axions are yet hypothetical particles postulated from quantum chromodynamics. They are candidates for dark matter and also might be produced in the Sun's core when X-rays scatter off electrons or protons in the presence of strong electric fields. The CERN Axion Solar Telescope (CAST) is using a strong magnetic field from a decommissioned test magnet used at the Large Hadron Collider to search for possible interactions of the particles with the magnetic field resulting in X-rays. Since 2003 no evidence for solar axions has been found, however, the limits for the search range could be refined.

To fully explore the solar radiation spectrum from the Sun, such as the UV and X-ray regime where important processes in the solar atmosphere take place, space-borne observatories in order to cover the ranges blocked by the terrestrial atmosphere are needed (cf. **Figure 1**). Additionally, observing from different vantage points than from ground-based stations only is of great interest. The missions orbiting the Sun out of the ecliptic plane offering a view on the solar poles are special examples, as was the STEREO mission, observing from two spacecraft simultaneously.

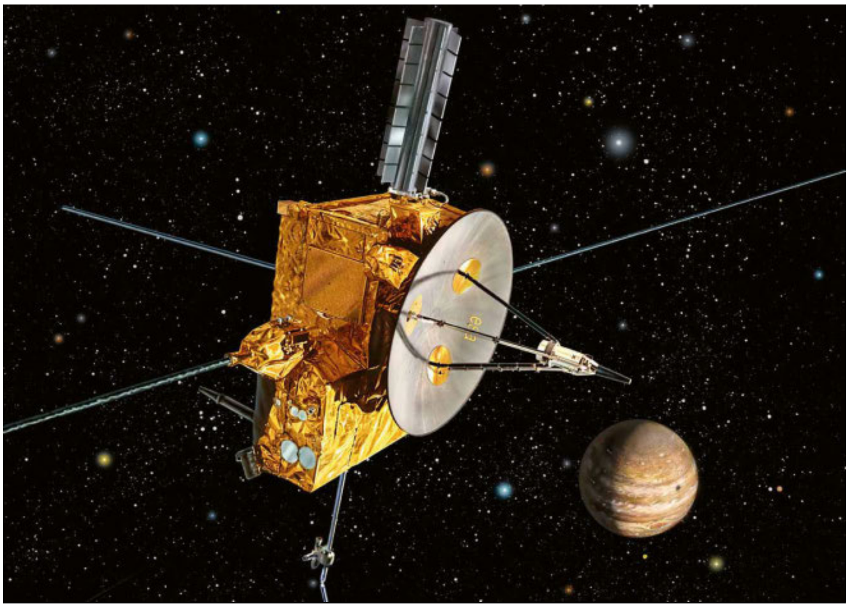


Figure 2: Ulysses, artist's view. On the right and left diagonal, the radio plasma antennae can be seen, downwards pointing is the magnetometer boom, on the front the high-gain antenna. (Source: ESA/NASA, Public domain, via Wikimedia Commons).

In the following, a description of the (arguably) most influential solar space missions will be presented, not claiming completeness but rather trying to present an overview. In fact, most of the missions, in particular the recent ones, are worth of being featured on their own. This will probably be the case in a later *Spatium* issue.

Already in the 1930s, experiments with balloon-borne instrumentation were performed in Germany by Erich Regener (1881 to 1955) to measure the higher-energetic parts of the solar spectrum. Supported by Wernher von Braun (1912 to 1977), he also developed instrumentation to be flown on rockets, e.g. on an A4 rocket, that was also used as V2 missile. A barrel-shaped container (the "Regener Tonne") was equipped with barometers and temperature sensors as well as spectrographs to observe the solar spectrum at high altitude. The payload had been delivered to the launch site, Peenemünde, in early January 1945 and its adjustments and functional tests had been completed on 18 January. At that time, however, the increasing severity of the war prohibited an A4 flight for scientific purposes, and the history of sounding rockets for solar science proceeded in the USA afterwards. A bit more on the history can be found in the introductory chapter of Huber et al (2013).

During the 1960s, NASA launched a series of spacecraft, the Pioneer probes, in order to investigate interplanetary space. Apart from observations of Jupiter, Saturn and Venus, they observed solar magnetic fields, particles and cosmic rays. The OSO series (Orbiting Solar Observatory) was another set of space telescopes launched in the 1960s and 1970s.

Together with the German Aerospace Centre DLR, in the 1970s NASA launched the two Helios probes (Helios 1 and Helios 2). Both probes collected important data about solar wind processes and the particles that make up the interplanetary medium and on cosmic rays. The Helios project set a maximum speed record for spacecraft of 70.22 km/s (252 792 km/h). Helios 2 performed the closest flyby of the Sun (to within 42 million kilometres) of any spacecraft, the record to last until October 2018. The probes are no longer functional, but as of 2023 remain in elliptical orbits around the Sun. On the Skylab, the Apollo Telescope Mount (ATM, a crewed solar observatory, operating 1973 and 1974) was providing measurements of the solar wind and the corona.

In 1980, the Solar Maximum Mission (SMM) was launched by NASA, in particular to study high-energy events such as flares. Its payload was mainly targeting the X-ray part of the spectrum, but also included an irradiance monitor. Shortly after the first successful measurements, its attitude control failed, and it was left in standby for three years. In April 1984, it was refurbished in a Space Shuttle mission, which was a remarkable endeavour, being the first orbiting, uncrewed satellite to be repaired in space. Afterwards, it was delivering data for five more years.

Ulysses (see **Figure 2**), a joint venture of ESA and NASA, was launched in 1990, designed to orbit over the solar poles and study it at all heliocentric latitudes. This required to change its orbital inclination and leave the plane of the solar system, which greatly exceeded the power available by any launch system. It could be achieved by a gravity-assist (so-called "swing-by") manoeuvre around Jupiter. Ulysses was equipped with a comprehensive range of twelve scientific instruments to detect and measure solar wind ions and electrons, magnetic fields, energetic particles, cosmic rays, natural radio and plasma waves, cosmic dust, neutral interstellar gas, solar X-rays, and cosmic Gamma Ray Bursts. It orbited the Sun three times and performed six polar passes. The mission concluded on 1 July 2008.

Important results from the Ulysses spacecraft included measurements of interactions of the solar magnetic field with the heliosphere, measurements of the strength of the solar wind, and the abundance of "dust" particles from deep space, i. e., from outside the solar system. It was also the first spacecraft to observe hints of magnetic "switchbacks", which are sudden reversals in the magnetic field carried by the solar wind.

The Japanese mission Yohkoh ("Sunbeam", pre-launch working name Solar-A) was launched in 1991 and observed a full solar activity cycle. The scientific instruments were designed to measure in the higher-energy range, being a soft X-ray telescope (SXT) and a hard X-ray telescope (HXT), a Bragg crystal spectrometer (BCS) for optical diagnosis of ultra-high-temperature plasma, and a wide-band spectrometer (WBS) to conduct spectroscopic observation of the wide-energy region from soft X-rays to gamma rays.

2. SOHO

The Solar and Heliospheric Observatory, SOHO (see **Figure 3**), a project of collaboration between ESA and NASA, has been one of the flagships of solar research. Launched in 1995 and having undergone several extreme adventures during its long and successful life, astonishingly, some of its instruments are still delivering data at the time of writing (November 2023). SOHO moves around the Sun on the sunward side of Earth, orbiting around the Lagrange point L1. At this position in space, the gravitational fields of the Sun and Earth cancel each other. A spacecraft enters an orbit around L1 as if the Lagrange point were an "invisible planet". Due to the instability of this orbit, small trajectory errors will grow quickly, and as a result, spacecraft must perform "station keeping" manoeuvres roughly once a month to keep them in the correct orbit.[2]

Its twelve instruments were designed to study the Sun from core to corona, as well as the heliosphere and the Sun-Earth interaction, the space weather.

One of the main mission objectives has been the study of the structure and dynamics of the solar interior, via investigating oscillations that are mainly driven by sound waves.[3] Oscillation modes and waves were probed for example by the Michelson Doppler Imager/Solar Oscillations Investigation MDI/SOI in the visible spectral range around 600 nm. On the solar surface, the

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2 The spacecraft are not placed in the Lagrange points themselves, but guided along a halo orbit around L1, where their station keeping, i. e., orbit stability, is energetically less demanding than if their position were maintained in the Lagrange points themselves.

3 The science of studying the structure and dynamics of the Sun through its oscillation modes is called helioseismology. Helioseismology, like terrestrial seismology (or asteroseismology), studies wave motions that are excited in the body's (Earth or Sun or star) interior and propagate through a medium. Whereas on Earth, seismic waves are generally due to earthquakes, no such source exists on the Sun, but the various modes are mainly due to processes in the larger convection zone. Solar oscillation modes are interpreted as resonant vibrations of a roughly spherically symmetric self-gravitating fluid in hydrostatic equilibrium, for example as a pattern of standing sound waves, that can probe the medium in which they form.

waves appear as up and down oscillations of the gases, observed as Doppler shifts of spectrum lines. If one assumes that a typical visible solar spectrum line has a wavelength of about 600 nm and a width of about 10 pm (1 pm = 10^{-12} m), then a velocity of 1 m/s shifts the line about 0.002 pm. Measuring the acoustic waves inside the Sun as they perturb the photosphere, one can study the structure and dynamics of the Sun's interior. Just like seismologists use the way earthquakes travel through Earth's interior to study our planet's structure, solar physicists use helioseismology to study the Sun's interior structure by tracking the way waves move throughout the star. Unlike Earth, where seismic events are typically distinct, the Sun is constantly ringing with sound waves because of the continuous convection of solar material going on beneath the surface. MDI also measured the longitudinal component of the Sun's magnetic field.

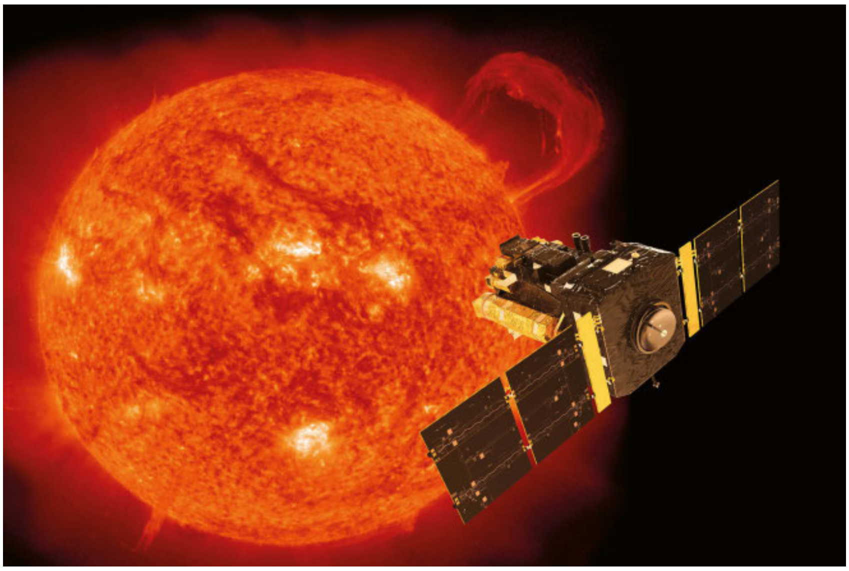


Figure 3: Artist's view of the SOHO spacecraft, projected on to a solar image featuring a huge prominence. The corresponding image was taken by SOHO's Extreme Ultraviolet Imaging Telescope (EIT) on 14 September 1999 at 304 Å wavelength. Prominences are huge clouds of relatively cool dense plasma suspended in the Sun's hot, thin corona. At times, they can erupt, escaping the Sun's atmosphere. Emission in this spectral line shows the upper chromosphere at a temperature of about 60 000 K. Every feature in the image traces magnetic field structure. (Source: ESA/NASA).

The Extreme ultraviolet Imaging Telescope (EIT) provides full disk images of the Sun at four selected wavelength bands in the extreme ultraviolet, mapping the plasma in the low corona and transition region at temperatures between 60 000 K and 3 000 000 K. **Figures 3, 4** and **6** contain full-disk images taken by EIT.

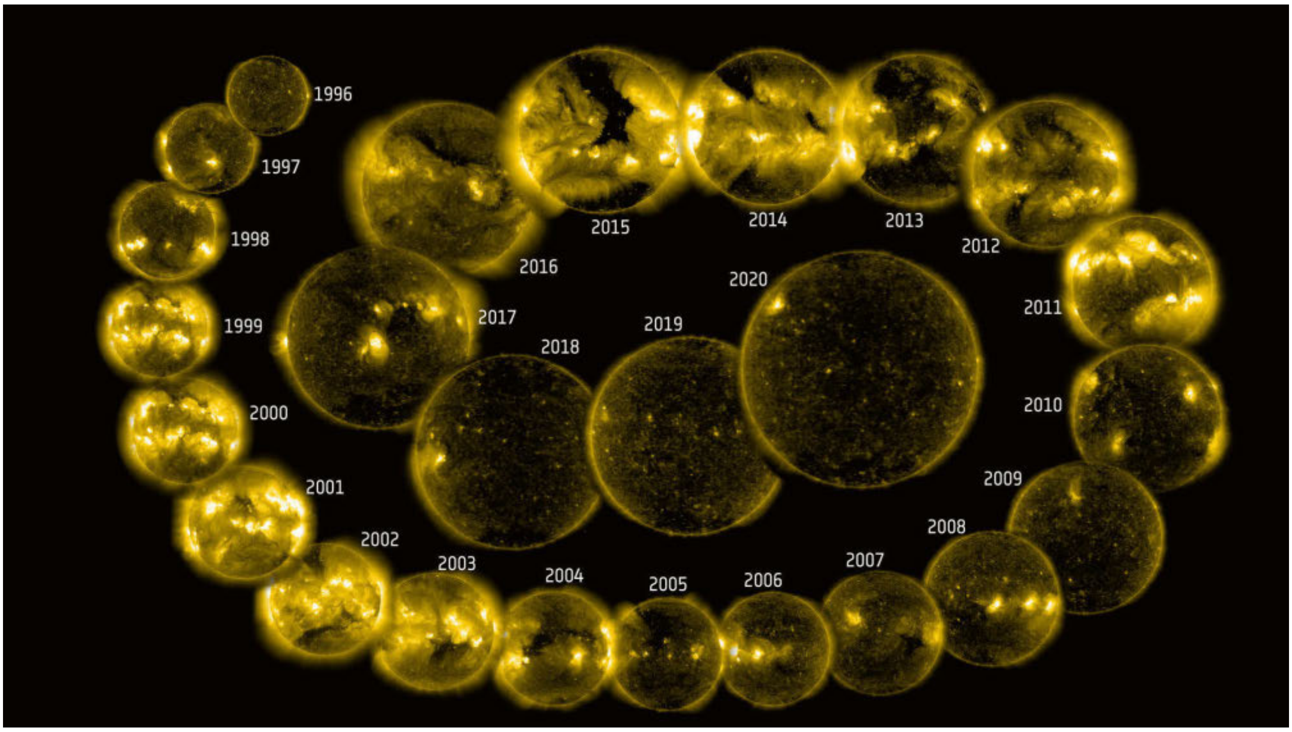
The Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument was used to perform detailed spectroscopic plasma diagnostics (flows, temperature, density, and dynamics) of the solar atmosphere, from the chromosphere through the transition region to the inner corona, over a temperature range from 10 000 K to 2 000 000 K and above. Similarly, the Coronal Diagnostic Spectrometer (CDS) detected emission lines from ions and atoms in the solar corona and transition region, providing diagnostic information on the solar atmosphere, especially of the plasma in temperature range from 10 000 K to more than 1 000 000 K. Both instruments, although of different technical design, partially observed in overlapping wavelength bands, and their measurements could well be compared, helping for quality assurance and calibration.

The UltraViolet Coronagraph Spectrometer (UVCS) also measured in ultraviolet light of the solar corona (however, between approximately 1.3 and 12 solar radii from the centre) by creating an artificial solar eclipse, blocking the bright light from the solar disk and allowing observation of the less intense emission from the extended corona, providing information about the microscopic and macroscopic behaviour of the highly ionised coronal plasma.

The Variability of Solar Irradiance and Gravity Oscillations (VIRGO) instrument, designed at the Physikalisch-Meteorologisches Observatorium at Davos (PMOD) characterised solar intensity oscillations and measured the total solar irradiance (TSI, known as the "solar constant") to quantify its variability over periods of days to the duration of the mission and to contribute to its long-term monitoring. The Comprehensive Suprathermal and Energetic Particle Analyzer (COSTEP) and Energetic and Relativistic Nuclei and Electron experiment (ERNE) instruments were built to detect and classify energetic particle populations of solar, interplanetary, and galactic origin. Global Oscillations at Low Frequencies (GOLF) studies the internal structure of the Sun by measuring velocity oscillations over the entire solar disk. For the solar wind and heliospheric studies, the Charge, Element, and Isotope Analysis System (CELIAS) samples the solar wind and energetic ions of solar, interplanetary, and interstellar origin, analysing the density and composition of particles present in this solar wind. The Large Angle and Spectrometric Coronagraph (LASCO) observes the outer solar atmosphere from near the solar limb to a distance of 21 million kilometres, that is, about one seventh of the distance between the Sun and the Earth. LASCO blocks direct light from the surface of the Sun with an occulter, creating an artificial eclipse. LASCO has also become SOHO's principal comet finder. The Solar Wind Anisotropies (SWAN) is the only remote sensing instrument on SOHO that does not look at the Sun. It watches the rest of the sky, measuring hydrogen that is "blowing" into the Solar System from interstellar space. By studying the interaction between the solar wind and this hydrogen gas, SWAN determines how the solar wind is distributed. As such, it can be qualified as SOHO's solar wind "mapper".

In many aspects, the SOHO mission was a game changer for solar physics. Never before had telescope-spectrometer combinations been able to generate high-resolution images and time series of the full solar disk or parts of it, moni-

Figure 4: SOHO has been observing the Sun for 25 years. In that time, it has observed two of the Sun's 11-year sunspot cycles. This montage of 25 images in the 284 Å wavelength band captured by the spacecraft's Extreme Ultraviolet Imaging Telescope shows gas with a temperature of about two million degrees Celsius in the Sun's corona. (Source: SOHO/ESA/NASA).



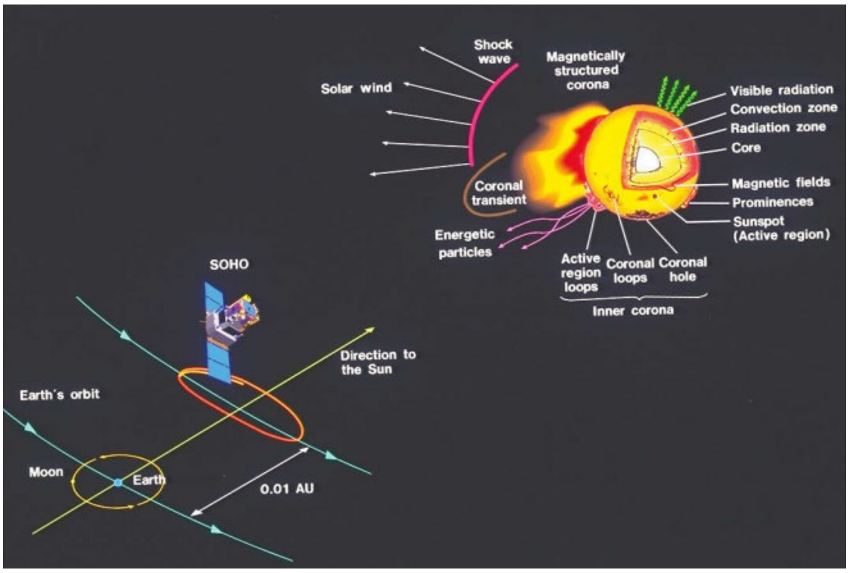
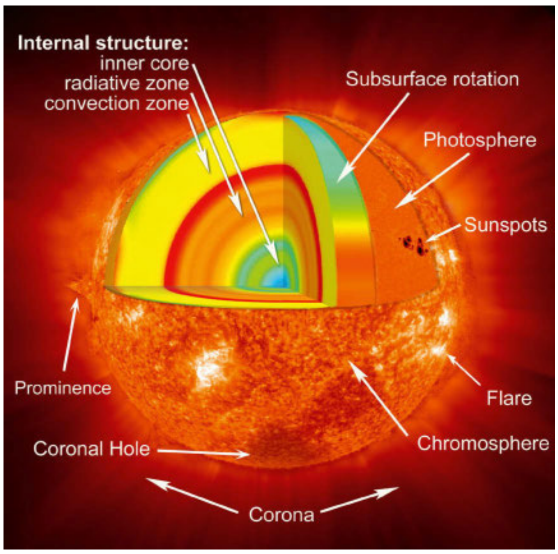


Figure 5: The L1 Lagrangian point, 1.5 million km out on the Earth-Sun line, the "pole position" to the Sun (Source: SOHO/ESA/NASA).

tored sunspot evolutions and coronal mass ejections, and combine all these data. However, relatively early in its mission, SOHO nearly experienced a catastrophe. During a routine calibration procedure in June 1998, in fact during the "housekeeping" procedure to maintain the orbit around L1 about 1.5 million kilometres from Earth (see **Figure 5**), the operations team lost contact with the spacecraft. With the help of a radio telescope in Arecibo, the team eventually located SOHO and brought it back online by November of that year. However, complications from the near loss emerged just weeks later, when all three gyroscopes – which help the spacecraft point in the right direction – failed. The spacecraft was no longer stabilised. The team's software engineers developed a new programme that would stabilise the spacecraft without the gyroscopes. SOHO resumed normal operations in February 1999, becoming the first spacecraft of its kind to function without gyroscopes. Actually, as of November 2023, although most of the instruments have ended their observation, some are still providing useful data.

Some of SOHO's spectacular results were revealing the first images ever of a star's turbulent convection zone and of the structure of sunspots below the surface. It also provided the most detailed and precise measurements of the temperature structure, the interior rotation, and gas flows in the solar interior (see **Figure 6**). SOHO discovered new dynamic solar phenomena such as coronal waves and solar tornadoes, via its combination of disk-viewing and coronal instruments, it revolutionised the ability to forecast space weather by giving up to three days' notice of Earth-directed disturbances, and playing a lead role in the early warning system for space weather. Moreover, it monitored the total solar irradiance TSI as well as variations in the extreme ultraviolet flux, both of which are important to understand the impact of solar variability on Earth's climate.

Figure 6: Left interior cutaway: variations in the speed of sound in the deep interior as gauged by helioseismic measurements by SOHO/MDI and SOHO/VIRGO. The distinct red layer, about a third of the way down from the surface to the Sun's centre, shows unexpectedly high temperatures at the transition between the turbulent outer region (convection zone) and the more stable region inside it (radiative zone). The very core of the Sun (blue) may be 0.1 % cooler than the expected 15 million K. Right interior cutaway: solar interior rotation (red: faster rotation, blue: slower rotation). The equatorial regions rotate faster than the polar regions, all the way down to the bottom of the convection zone. The radiative zone below appears to rotate at the same angular velocity (solid body rotation). Outer cutaway: SOHO/MDI visible-light image showing sunspots in the photosphere. Wrap-around: SOHO/EIT He II 304 Å image showing the Sun's outer atmosphere (transition region) at a temperature of about 60 000 K.
(Source: SOHO/ESA/NASA).



3. WIND, ACE, and TRACE

NASA's Wind is a spin-stabilised spacecraft launched on 1 November 1994 and placed in a halo orbit around the Sun-Earth L1 Lagrange point. The spacecraft observes the solar wind that is about to impact the magnetosphere of Earth. Its payload consists of eight instruments for measuring energetic particles, radio and plasma waves, magnetic fields and gamma rays. The original projected lifetime of the vehicle was anticipated to be three to five years, but Wind continues to be largely operational in 2023. One gamma-ray spectrometer has been turned off, and a couple of detectors on another instrument are non-functional.

NASA's Advanced Composition Explorer (ACE) spacecraft was designed to study space-borne energetic particles, also from the Sun-Earth L1 Lagrange point. It was launched in 1997 and has a payload of nine instruments, measuring particles form the solar wind and cosmic rays, such as mass spectrometers, isotope analysers, and additionally a magnetometer. It is also still operational as on November 2023.

The Transition Region and Coronal Explorer (TRACE) was a NASA heliophysics and solar observatory designed to investigate the connections between fine-scale magnetic fields and the associated plasma structures on the Sun by providing high-resolution images and observation of the solar photosphere, the transition region, and the solar corona. A main focus of the TRACE instrument was the fine structure of coronal loops low in the solar atmosphere. TRACE was the third spacecraft in the Small Explorer programme, launched in April 1998, and obtained its last science image on 21 June 2010.

4. RHESSI, STEREO, and Hinode

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI, originally High Energy Solar Spectroscopic Imager, HESSI), launched in February 2002, was a NASA solar flare observatory built with significant contribution from the Swiss Paul Scherrer Institut where the main parts of the imaging telescope assembly were constructed and tested. Its primary mission was to explore the physics of particle acceleration and energy release in solar flares. It had been renamed after launch in honour of Reuven Ramaty, a pioneer in the area of high-energy solar physics. RHESSI was designed to image solar flares in energetic photons from soft X-rays (around 3 keV) to gamma rays (to 20 MeV) and at the same time to provide high-resolution spectroscopy. To reconstruct images from X-rays, which cannot be easily reflected or refracted with conventional optics, a special technique was used, employing nine rotational modulation collimators, each consisting of two sets of widely spaced, fine-scale linear grids. The entire spacecraft rotated at 15 rpm, and the grids blocked and unblocked any X-rays, modulating the photon signal in time. From the modulation pattern, the amplitude and phase of many spatial Fourier components over a full range of angular orientations could be retrieved, and images were then reconstructed from the set of measured Fourier components. RHESSI localised and measured numerous solar flare events, and it was the first satellite to image gamma rays from solar flares. It could also measure terrestrial gamma-ray flashes from thunderstorms. It stopped science operations after a communication fault in 2018, and re-entered Earth's atmosphere in April 2023.

NASA's STEREO (Solar Terrestrial Relations Observatory) mission has explored the advantages of stereoscopic view. The mission was launched in 2006, with the two identical A(head) and B(ehind) spacecraft each put into their own orbits about the Sun, one ahead of Earth, one trailing Earth. The instruments on board consist of an imager in the extreme ultraviolet wavelength range and white-light coronagraphs to study the 3D shape and evolution of coronal mass ejections, as well as in-situ particle instruments and radio trackers. As the spacecraft continued to separate, the distance became too large to make stereoscopic images, but the data continued to be useful to derive information about the 3D structures of solar features. Unfortunately, control of STEREO B was lost in 2014, just before it was about to pass behind the Sun, but STEREO A continued in its orbit to pass by Earth again in 2023. Meanwhile, equivalent images from the NASA Solar Dynamics Observatory can be used for combination to once again make stereoscopic movies, with the added advantage of a much more active Sun.

Hinode ("Sunrise"), formerly Solar-B, is a Japan Aerospace Exploration Agency (JAXA) solar mission with US and UK collaboration. It is the follow-up mission to Yohkoh, and was launched in September 2006. It observes from a Sun-synchronous orbit[4]. It carries a suite of three instruments, one optical, the Solar Optical Telescope (SOT) which has been the first large space-borne optical telescope dedicated for solar studies, an X-ray Telescope (XRT), and an Extreme-Ultraviolet Imaging Spectrometer (EIS). The Hinode mission was planned to last three years, but the observatory continues to provide quality scientific data far beyond its original specifications.

5. Parker Solar Probe

NASA's Parker Solar Probe was launched in August 2018, and the spacecraft is gradually orbiting closer to the Sun's surface than any before it – well within the orbit of Mercury. The mission has been named for Eugene N. Parker (1928 to 2022), who contributed significantly to the modern understanding of the Sun. In the mid-1950s, he developed a mathematical theory that predicted the properties and geometry of the solar wind. In 2018, Parker became the first person to witness the launch of a spacecraft bearing his name. The spacecraft and its instruments are protected from the Sun by a 11.43 cm carbon-composite shield, which can withstand temperatures reaching nearly 1377 °C. To fly more than seven times closer to the Sun than any spacecraft before, it uses repeated gravity assists at Venus to incrementally decrease its orbital perihelion to achieve a final altitude above the solar surface of approximately 8.5 solar radii, 0.046 astronomical units or about 6 million kilometres. The spacecraft trajectory will include seven Venus flybys over nearly seven years to gradually shrink its elliptical orbit around the Sun, for a total of 24 orbits. The near-Sun radiation environment is predicted to cause spacecraft charging effects, radiation damage in materials and electronics, and communication interruptions, so the orbit will be highly elliptical with rather short times spent near the Sun. The probe has four instrument suites designed to study magnetic fields, plasma and energetic particles, and image the solar wind.

Touching the Sun

On 28 April 2021, Parker Solar Probe entered the magnetised atmosphere of the Sun, 13 million kilometres, about 18.8 solar radii, above the photosphere, crossing below the Alfvén critical surface[5] for five hours into plasma in casual contact with the Sun. Before that, only estimates of the position which marks the end of the solar atmosphere, the boundary of the corona, and the beginning of the solar wind were available, and put it somewhere between 10 and 20 solar radii from the surface. This event was described by NASA as "touching the Sun". During the flyby, Parker passed into and out

[4] A Sun-synchronous or heliosynchronous orbit, is a nearly polar orbit around a planet, in which the satellite passes over any given point of the planet's surface at the same local mean solar time. It precesses through one complete revolution each year, so it always maintains the same relationship with the Sun.

[5] The Alfvén surface is the boundary separating a star's corona from the stellar wind, defined as where the coronal plasma's Alfvén speed (velocity of propagation of Alfvén waves in the direction of the magnetic field; it is proportional to the magnetic field strength, and inversely proportional to the square root of the ion density) and the large-scale stellar wind speed are equal. At this critical surface the Sun's gravity and magnetic forces become too weak relative to the rising heat and pressure to contain the solar material. Parker Solar Probe became the first spacecraft that crossed the Alfvén surface of the Sun.

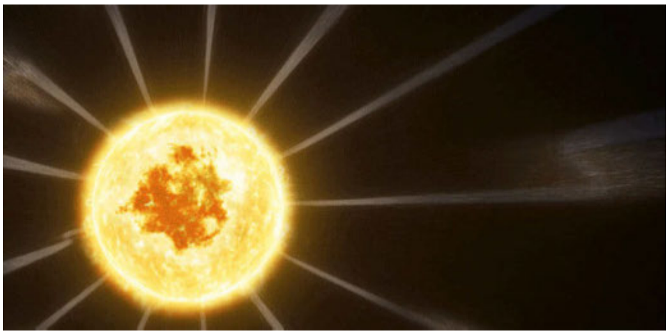


Figure 7: Artist's impression of Parker Solar Probe flying through a switchback, a zigzag structure in the solar wind. Parker encountered numerous features like these in the area of the solar wind, however, their number dropped down significantly when entering below the atmosphere into the corona.

of the corona several times, confirming that the critical surface is rather rough and spiky than flat and smooth (Kasper et al 2021).

As the probe passes around the Sun, it will achieve a velocity of up to 200 km/s, which will temporarily make it the fastest human-made object, almost three times as fast as the previous record holder, Helios 2, which also held the record so far of proximity to the Sun of a human-built object. On 27 September 2023, the spacecraft travelled at 176.5 km/s, fast enough to fly from New York to Tokyo in just over a minute. Like every object in an orbit, due to gravity the spacecraft will accelerate as it nears perihelion, then slow down again afterward until it reaches its aphelion. A recent study in Nature (Bale et al 2023) describes how measurements of Parker could provide strong evidence that the fast solar wind is accelerated via interchange reconnection (i. e., magnetic reconnection between open and closed magnetic fields in the low corona, see also **Figure 11** later) within magnetic field bundles.

Plasma and Alfvén waves

Although not easy to generate artificially by strong heating a neutral gas or subjecting it to a strong electromagnetic field, plasma is the most abundant form of ordinary matter in the Universe, mostly in stars (including the Sun), but also dominating the rarefied intracluster medium and intergalactic medium. Plasma is characterised by the presence of a significant portion of charged particles in any combination of ions or electrons. It is distinct from the other states of matter. In particular, describing a low-density plasma as merely an "ionised gas" is wrong and misleading, even though it is similar to the gas phase in that both assume no definite shape or volume. While gases interact only on short scales, for plasma collective phenomena are dominant, resulting in various types of plasma waves and other interactions. Moreover, the conductivity is extremely high in plasmas. Plasma exhibit behaviours similar to fluids and gases, but with added complexity of containing magnetic (and occasionally electric) fields. In 1942, Hannes Alfvén (1908 to 1995) combined the mathematics of fluid mechanics and electromagnetism to predict that plasma could support wave-like variation in the magnetic field, a wave phenomenon that now bears his name, Alfvén waves. This would become the foundational paper for the study of magneto-hydrodynamics, or MHD, for which Alfvén would receive the Nobel prize in 1970.

An Alfvén wave is a type of plasma wave in which ions oscillate in response to a restoring force provided by an effective tension on the magnetic field lines. Alfvén waves propagate in the direction of the magnetic field, and the motion of the ions and the perturbation of the magnetic field are transverse to the direction of propagation. Alfvén waves are supposed to play an important role in heating the solar corona.

6. Solar Dynamics Observatory

The NASA mission Solar Dynamics Observatory, SDO, was launched in 2010. Its primary goals are to investigate solar magnetism and activity: how the Sun's magnetic field is generated and structured, and how the magnetic energy is converted and released into the heliosphere. Three instruments form the scientific payload.

The Helioseismic and Magnetic Imager (HMI) extends the capabilities of the SOHO/MDI instrument with continual full-disk coverage at higher spatial resolution and new vector magnetogram capabilities.

The Atmospheric Imaging Assembly (AIA) images the solar atmosphere in multiple wavelengths to link changes in the surface to interior changes. Data include images of the Sun in 10 wavelengths every 10 seconds.

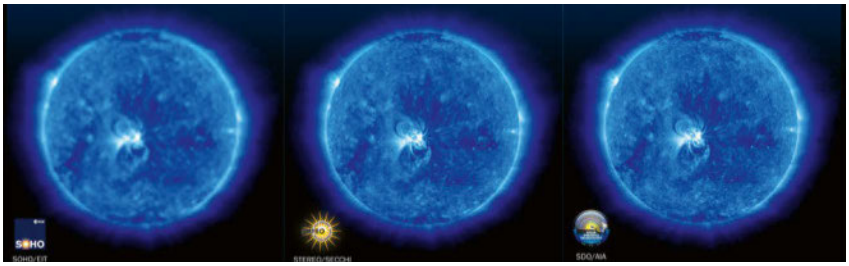
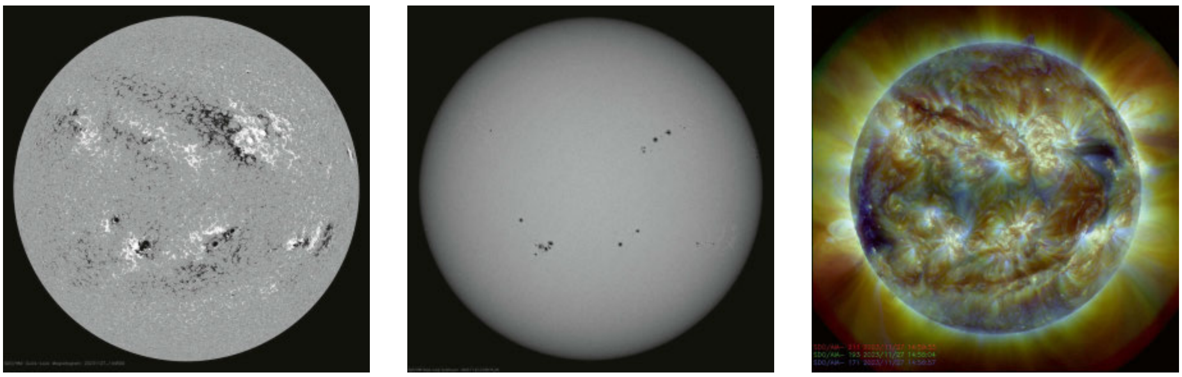


Figure 8: A comparison of the resolution capabilities of the SDO, STEREO, and SOHO spacecraft. SDO's AIA instrument (right image) has twice the image resolution than STEREO (middle image) and four times greater imaging resolution than SOHO (left image). The image cadence also varies. SDO takes one image every second. At best STEREO takes one image every three minutes and SOHO takes one image every twelve minutes.
(Source: NASA, SOHO/EIT, STEREO/SECCHI, SDO/AIA).

The Extreme Ultraviolet Variability Experiment (EVE) measures the solar extreme-ultraviolet (EUV) irradiance with unprecedented spectral resolution, temporal cadence, and precision. EVE measures the solar EUV spectral irradiance to understand variations on the timescales which influence Earth's climate and near-Earth space. **Figure 8** gives an impression of the evolution of solar instrumentation with respect to resolution.

It is highly recommended to visit the SDO webpages[6] hosted by NASA's Goddard Space Flight Center to get an impression of the high-resolution measurements of magnetic field and the various emission lines tracing the hot plasma in the different solar atmospheric layers (see **Figure 9**).

Figure 9: Left: The magnetic field as given from an HMI magnetogram; ***Middle:*** HMI intensitygram;
Right: a superposition of the three EUV wavelengths 171 Å, 193 Å, and 211 Å.
(All data are from 27 November 2023. Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.)



[6] https://sdo.gsfc.nasa.gov/data/ ("The Sun now", visited November 2023)

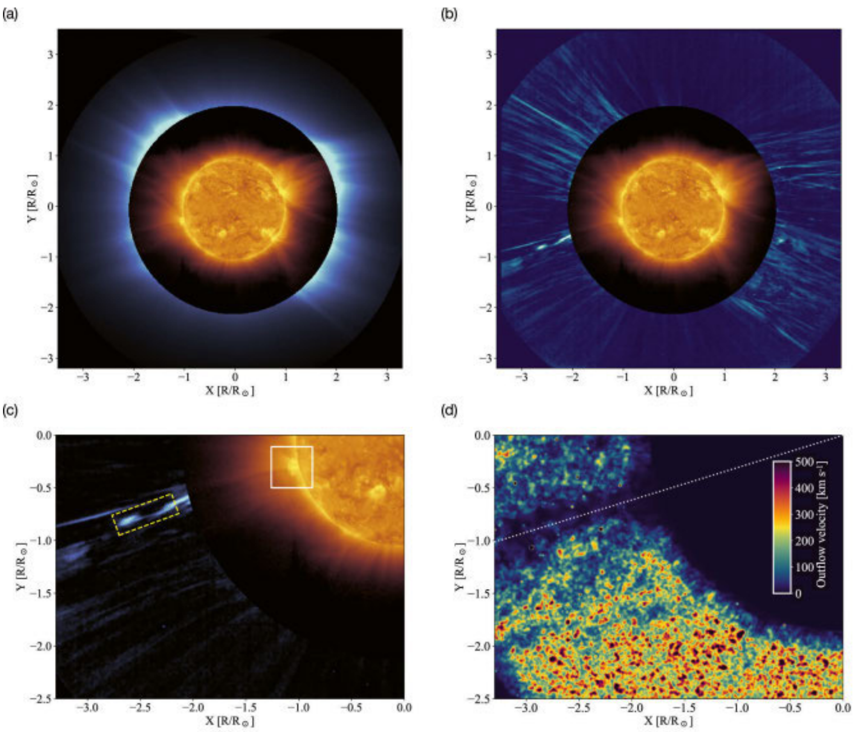
7. Solar Orbiter

The Solar Orbiter (SolO or SO) mission, an ESA project with a contribution from NASA, was launched in 2020. It will take approximately 3.5 years, using repeated gravity assists from Earth and Venus, to reach its operational orbit, an elliptical orbit with perihelion of 0.28 astronomical units and aphelion of 0.91 astronomical units. The first flyby of Venus took place in December 2020. Over the expected mission duration of seven years, it will use additional gravity assists from Venus to raise its inclination from 0° to 24°, allowing it a better view of the Sun's poles. If an extended mission is approved, the inclination could rise further to 33°. The science payload is composed of ten instruments: four heliospheric in-situ instruments (SWA – Solar Wind Plasma Analyser, EPD – Energetic Particle Detector, MAG – Magnetometer, RPW – Radio and Plasma Waves); and six remote-sensing instruments (PHI – Polarimetric and Helioseismic Imager, EUI – Extreme Ultraviolet Imager, SPICE – Spectral Imaging of the Coronal Environment, STIX – Spectrometer Telescope for Imaging X-rays, Metis – Coronagraph, SoloHI – Solar Orbiter Heliospheric Imager). One instrument, the STIX, providing imaging spectroscopy of solar thermal and non-thermal X-ray emission from 4 keV to 150 keV for quantitative information on the timing, location, intensity, and spectra of accelerated electrons as well as of high-temperature thermal plasmas, mostly associated with flares and/or microflares, has been largely developed and built in at the Fachhochschule Nordwest in Switzerland.

The switchback story – building on history

After a number of spacecraft had already flown through the puzzling regions of field line reversals (Helios, Ulysses, Parker), in particular Parker measuring the sudden magnetic field direction changes more numerous close to the Sun (see also **Figure 7**), it led to the suggestion that they were caused by S-shaped kinks in the magnetic field. Solar Orbiter finally was able to make the first ever remote-sensing observation of such a solar "switchback". The observation provided a full view of the structure, confirming its S-shaped character. Furthermore, the global perspective provided by the SO data indicated that these rapidly changing magnetic fields can

Figure 10: (a) Composite of the Metis-observed image of the solar corona within 3.5 $R_\odot$ FOV (blue) and the EUI image of the ultraviolet emission (yellow) as viewed from the SO vantage point on 25 March 2022 at 20:39 UT. ***(b)*** Same as in panel ***(a)***, but with the Metis observations radially filtered. ***(c)*** Zoom-in of panel ***(b)***; overlaid is the rectangular ROI where the time–distance analysis on the S-shaped structure was performed, and a white square indicating the loop system associated with active region AR 12972. ***(d)*** Coronal velocity map in the same FOV as in panel ***(c)***; the white dotted line marks the latitude relative to the S-shaped feature. The switchback corresponds to very slow moving plasma above an active region that has yet to release its stored energy.
(Source: ESA/SO, Figure 1 from Telloni et al 2022).



have their origin near the surface of the Sun. It originated above an active region with the related loop system bounded by open-field regions to the east and west. Observations, modelling, and theory provide strong arguments in favour of the interchange reconnection origin of switchbacks. **Figure 10** shows the measurements and **Figure 11** depicts the corresponding model that could be confirmed.

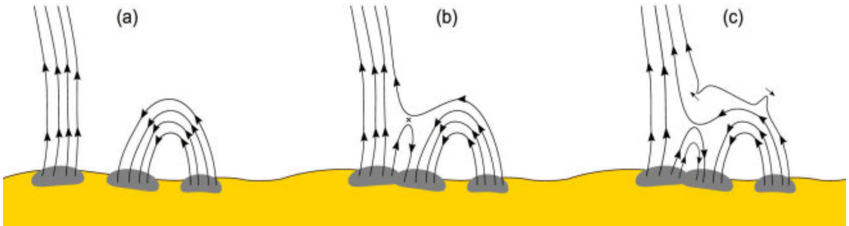
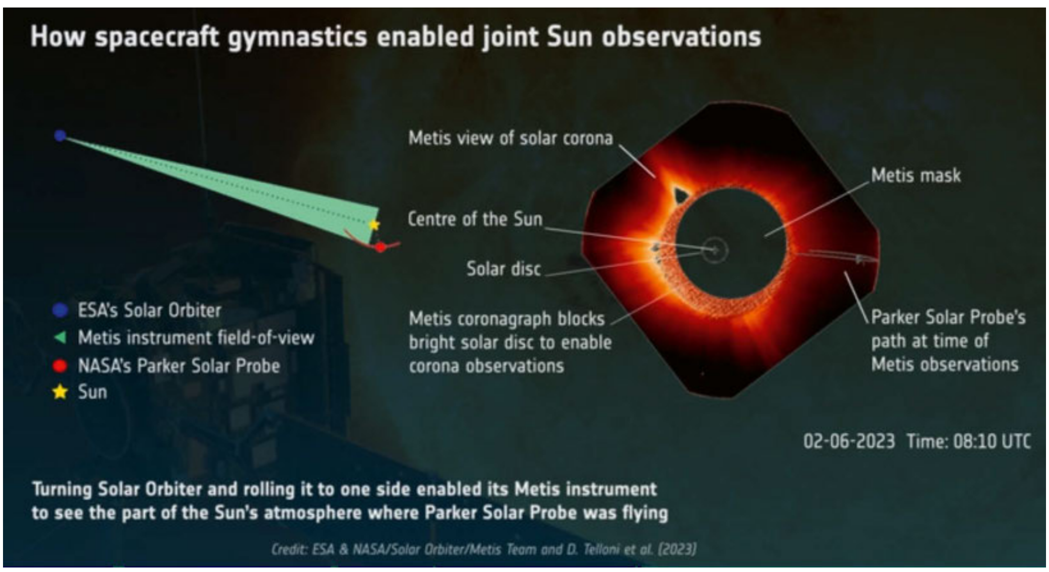


Figure 11: ***(a)*** Switchbacks have their footprint in active regions associated with sunspots and magnetic activity, where there are open (left) and closed (right) field lines. ***(b)*** When open and closed field lines interact (e.g., at point x), an S-shaped field line is created, producing a burst of energy. ***(c)*** As the field line responds, a kink – the switchback – is sent propagating out in opposite directions. (Source: ESA, Zank et al 2020).

Joining forces in the corona

In order to combine the forces of in-situ and remote sensing of Solar Orbiter and Parker Solar Probe, both instruments need to be perfectly aligned, meaning Parker in the field of view of SO's instruments. On 1 June 2022, both spacecraft would be nearly in perfect orbital position – however, SO's instruments pointing just a few degrees away. It thus required some pointing gymnastics for the SO to look at the right position, meaning a 45° roll and then pointing it slightly away from the Sun (see **Figure 12**). Luckily, this manoeuvre could be realised, and the roll and the offset pointing went ahead; Parker Solar Probe came into the field of view, and together the spacecraft produced the first ever simultaneous measurements of the large scale configuration of the solar corona and the microphysical properties of the plasma. This resulted in the first combined remote (by the SO Metis coronagraph) and in-situ measurements (by Parker's plasma and magnetic field instruments) of the same coronal flow, and thus, together with magnetohydrodynamic equations, an estimate of the coronal heating rate at this particular position.

Figure 12: Solar Orbiter's spacecraft orbit manoeuvring for combined remote and in-situ observations of the corona, together with Parker Solar Probe. (Source: ESA/NASA, Telloni et al 2023).



8. Outlook

It is amazing how many of the "old workhorses" of the solar spacecraft fleet are still in good condition and sending back data, given the rough environments they are exposed to. This is fortunate, as with several missions in operation, coordinated measurements, involving various instruments as well as ground-based observatories are possible.

Engineering and quality control, testing and calibration, as well as utmost cleanliness during assembly, transport and launch are necessary conditions for successful operation, and new missions can profit from lessons learnt from older ones.

Building on the technology and experience form earlier missions, for example Parker Solar Probe and Solar Orbiter successively joined observing forces and used their complementary instruments and measurements to refine some boundaries for coronal heating rates.

Still, some of the most interesting questions remain to be solved, although recent combined high-resolution observations shed some light into the coupling of the magnetic processes leading to heat transfer from the photosphere into the corona.

The Indian Space Research Org (ISRO) launched Aditya-L1 on 2 September 2023, with a solar coronagraph on board as main payload. In the future, probably also small and compact missions such as CubeSat missions will deliver data for solar and heliospheric research, and for sure, there is more to come from the current missions.

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Web resources:

We acknowledge various webpages from ESA and NASA, as well as Wikipedia.

SPATIUM

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