Solar Space Missions: present and future

Sami K. Solanki[1,2]

[1]Max-Planck-Institut für Sonnensystemforschung
Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
solanki@mps.mpg.de, www.mps.mpg.de/homes/solanki
[2]School of Space Research, Kyung Hee University
Yongin, Gyeonggi 446-701, Korea

Eckart Marsch

Max-Planck-Institut für Sonnensystemforschung
Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
marsch@mps.mpg.de, www.mps.mpg.de

Abstract

The Sun is the only star that we can spatially resolve sufficiently to study physical processes related to convection, turbulence and magnetism at the relevant spatial scales. The promise of fundamental physical insights into the workings of the Sun, which are of relevance to astrophysics far beyond the Sun itself, has in the past led to the launch of a number of space missions dedicated to studying the Sun. Also in the future an equally rich ensemble of exciting missions are expected to fly.

1 Introduction: The fascination of the Sun

The last decade has produced a revolution in the way we view the Sun. No longer does it appear as a structureless, invariant, boring star, but we know now that it displays structures at all scales, right down to the highest possible spatial resolution of approximately 100 km on the Sun's surface. Structures are visible at all wavelengths, and all of them are variable in time on scales ranging from seconds to the total length of observations. Such structures and their associated dynamic phenomena include sunspots, faculae, granules, magnetic bright points, chromospheric fibrils, spicules, flares, coronal mass ejections and many others features. Some examples of the myriad phenomena visible when observing the Sun with modern instruments and techniques are illustrated in Figs. 1 to 8, with Fig. 1 showing a small sunspot and the associated faculae, Fig. 2 chromospheric Ca K fibrils in a small active region, Fig. 3 Hα fibrils in an active region, Fig. 4 spicules and a prominence at the solar limb, Fig. 5 magnetic loops in an emerging flux region, Fig. 6 a stereoscopic

Reviews in Modern Astronomy 21. Edited by S. Röser

ISBN: 978-3-527-40910-5

Figure 1: A small sunspot (dark structure) located between the centre of the solar disk and the limb, as well as bright facular structures (bright sides of granules). Image taken with the Swedish Solar Telescope and kindly provided by V. Zakharov.

image (anaglyph) of the whole solar disk, Fig. 7 post-flare loops, and Fig. 8 the solar corona and a coronal mass ejection.

These fascinating and beautiful phenomena have become visible due to significant advances in instrumentation, both ground-based and space-borne, which have taken place in the last 10-15 years. On the ground the use of adaptive optics, now installed at various telescopes such as the Swedish Tower Telescope on the Canary island of La Palma, the German Vacuum Tower Telescope on the neighbouring island of Tenerife and the Dunn Tower on Sac Peak in the United States, has greatly enhanced the mean quality of the data. In space, missions such as SOHO, Ulysses, Yohkoh, TRACE, RHESSI, STEREO and Hinode have provided new and innovative windows to the Sun and revolutionized our view of our star.

It is remarkable that so many of the dynamic and often energetic and violent phenomena, of which some were introduced above (and a whole zoo of further ones that cannot be described here for lack of space), are dominantly driven by a single quantity, the Sun's magnetic field. It is produced in the solar interior by a dynamo process and evolves in a complex manner through its interaction with different flow

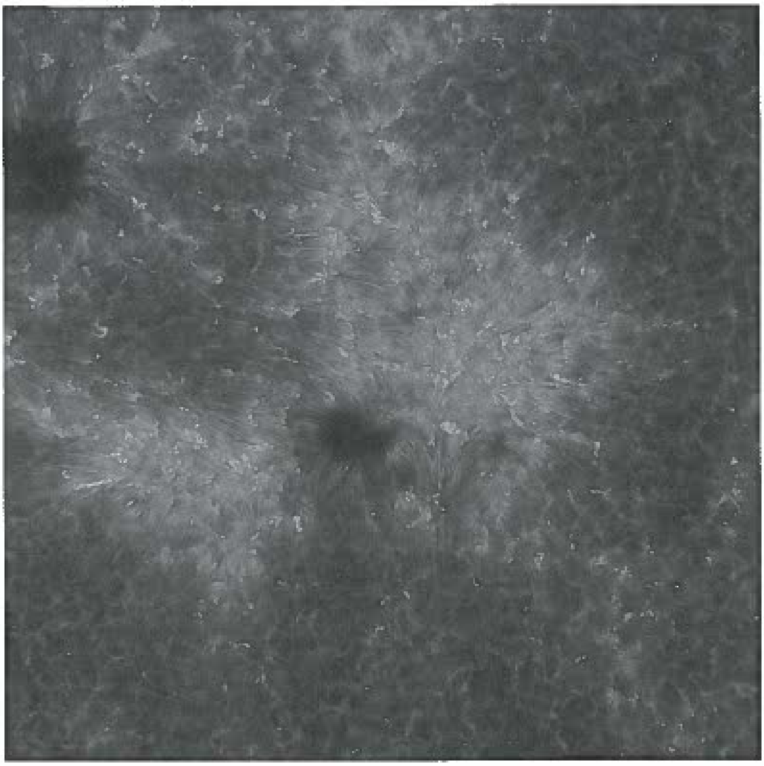

Figure 2: Part of a small active region in the light of the chromospheric Ca K line, displaying many elongated fibrils that most likely delineate magnetic field lines passing from the solar interior, through the photosphere into the chromosphere. The dark regions are solar pores. From Pietarila et al. (2009).

fields, primarily the turbulent convection, and the global differential rotation and meridional circulation.

However, by studying the Sun we not only have a chance to explore and finally to understand these fascinating phenomena in their own right, but also can, by transfer of knowledge, provide basic insights into physical processes taking place throughout the universe, in objects as diverse as cool stars, accretion disks around black holes and jets in active galactic nucleii. The advantage of investigating plasma and radiation processes on the Sun is that many of the large-scale phenomena, such as coronal mass ejections, are triggered by small-scale processes, such as magnetic reconnection. Due to the proximity of the Sun, its features at small spatial scales can be observed at high cadence (the latter due to the large photon flux), in contrast to any remote star or extra-solar astrophysical system.

A further important reason for studying the Sun is that it is the most prominent of the rare astrophysical objects that have a direct influence on our natural and technical environment and on human society. In particular the eruptive variant of the solar

Figure 3: A detail of an active region imaged in the Hα line of hydrogen. Data obtained at the Swedish Solar Telescope on 4th of October 2005. Image courtesy of the Institute of Theoretical Astrophysics, University of Oslo.

wind (coronal mass ejections) carries energetic charged particles to Earth, which can induce changes in the Earth's magnetic field, interact with the plasma in the Earth's magnetosphere and ionosphere and produce such conspicuous phenomena as aurorae. These particles and the currents induced by them can influence technical systems, in particular on satellites in exposed locations in space, but also on the ground, in particular at high geographical latitudes.

In addition, the changes in the radiative output of the Sun affect the Earth's atmosphere on longer time scales. The higher flux of ultraviolet (UV) light during the maximum of solar activity causes the upper atmosphere of the Earth to expand, thus greatly increasing the air drag on satellites in low-Earth orbit and causing some of them to spiral towards the ground in a disproportionately short time. Changes in the Sun's total and spectral irradiance also contribute to climate change (at around the 0.2° level over a solar cycle, Camp and Tung 2007) and may have contributed to the global warming in the first eight decades of the 20th century.

Figure 4: A fraction of the solar limb (indicated by the slightly curved, nearly horizontal dark line) recorded in the Ca II H line, showing spicules, a sunspot, and a prominence. Image taken by the Solar Optical Telescope (SOT) onboard the Hinode spacecraft. Image kindly provided by T.J. Okamoto, from Okamoto et al. (2007).

2 A global strategy to observing the Sun

The Sun presents us with a range of phenomena which are as yet unexplained. Thus, we still neither know what makes the corona glow at a temperature of millions of kelvin, nor how exactly the solar wind is accelerated to its speed of hundreds of kilometers per second. We are still fighting to find the answers to such basic questions as to how fast the solar core rotates, why sunspots are only grey and not pitch black in spite of their strong fields, or by how much the Sun has brightened over the last three centuries (a question of great relevance for our understanding of the global warming of the Earth).

In order to make significant strides towards answering these questions, it is necessary to observe the Sun at a wide range of wavelengths and with a whole battery of (highly specialized) instruments required because of the very large range over which key physical parameters of the Sun change. For example, the density varies by nearly 30 orders of magnitude from the core of the Sun to the outer reaches of the Heliosphere (i.e., the regime dominated by the solar wind). Similarly, the temperature spans 4 orders of magnitude just within the Sun's atmosphere.

The types of observations required to make progress in solar physics are:

- High resolution: Observations achieving a high spatial resolution are a must, since the magnetic field produces structures often at the limit of the best currently available spatial resolution (e.g., the sizes of magnetic flux concentrations in the solar photosphere, thickness of coronal loops, and length scales of magnetic reconnection sites).
- Polarimetry: Measurements of the magnetic field require recordings of the po-

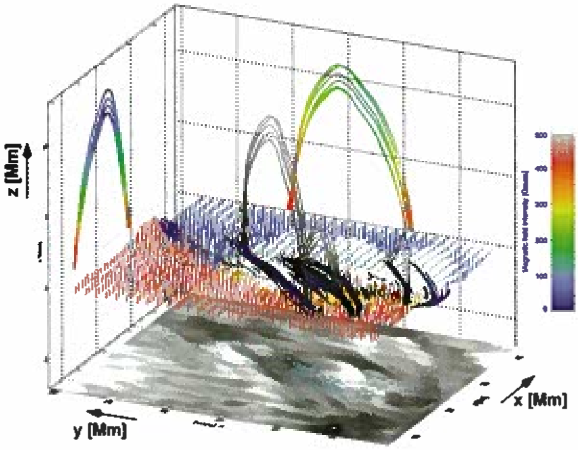

Figure 5: Structure of magnetic loops in an emerging flux region, reconstructed from the inversion of spectropolarimetric observations of an emerging flux region in the He I 10830 Å triplet recorded with the TIP instrument on the VTT, Tenerife. The gray-scale image at the bottom of the plot shows the He I line strength (darker means more absorption). The set of short lines above it corresponds to the opposite magnetic polarities (red and blue). The 3-D structure of the young loops is represented by the grey curves, while the coloured projections of these loops indicate the magnetc field strength (left projection and left side of the colour scale) and the LOS flow velocity (right projection). From Solanki et al. (2003).

larized states of light. Since the magnetic field is the driver of solar activity, it is of fundamental importance to carry out such measurements.

- Multi-wavelength observations: Many phenomena happen over different layers of the Sun's atmosphere, which are visible in radiation emitted at different wavelengths. For example, the Sun's surface (and interior, via helioseismology) is best seen at visible wavelengths, while the solar corona is best observed in the extreme UV (EUV) light or in X-radiation (but also emits radio waves).
- Stereoscopy: The often complex three-dimensional structure of the magnetic field in the solar atmosphere forms a skeleton on which the multi-million-kelvin plasma attaches itself. Stereoscopy is necessary to uncover the magnetic and plasma structures in the solar atmosphere, and is of advantage to determine their 3-D nature. This requires simultaneous observations of a particular part of the solar atmosphere from two different viewing directions (being, e.g., 10-15 degrees apart).
- Observations from novel vantage points:
  - A spacecraft flying close to the Sun can directly sample the material of the Sun's outer corona.
  - Observations of the Sun from high heliographic latitudes access the solar poles far better than from the ecliptic.

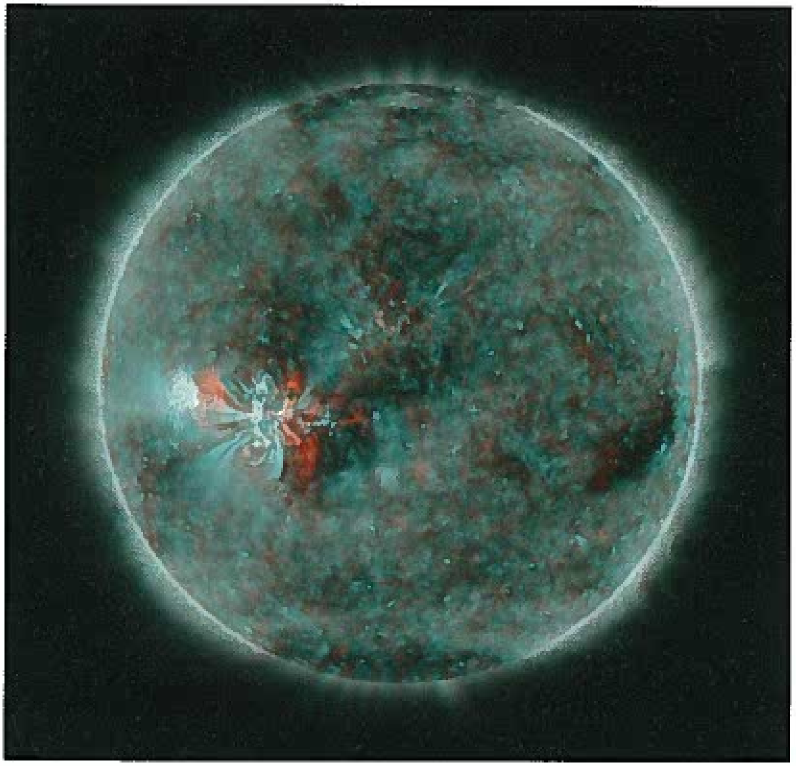

Figure 6: A red/cyan anaglyph of the full solar disk produced from two images in the Fe IX 171 Å line provided by the EUVI telescopes (part of the SECCHI imaging package) on the STEREO A and B spacecraft. Figure kindly provided by B. Podlipnik.

- Observations from a spacecraft located 90° ahead or behind the Earth (in the Earth's orbit) allow coronal mass ejections to be followed from the Sun all the way to the Earth.
- Finally, a spacecraft located roughly behind the Sun reveals its side hidden to Earth and allows us to predict solar features that will soon appear from behind the limb.
- In situ observations: the Sun sends us not just electromagnetic radiation, but also particles, which reflect the elemental composition of the solar corona, but also carry signatures of the various acceleration processes that ejected them from the Sun. Mass spectrometers of different designs can be used to determine not just the composition of the solar wind and its general properties but also the relevant properties of energetic particles.

Solar physicists world-wide have employed a concerted approach to attacking the open problems in solar physics, taking into account the observational requirements and possibilities outlined above.

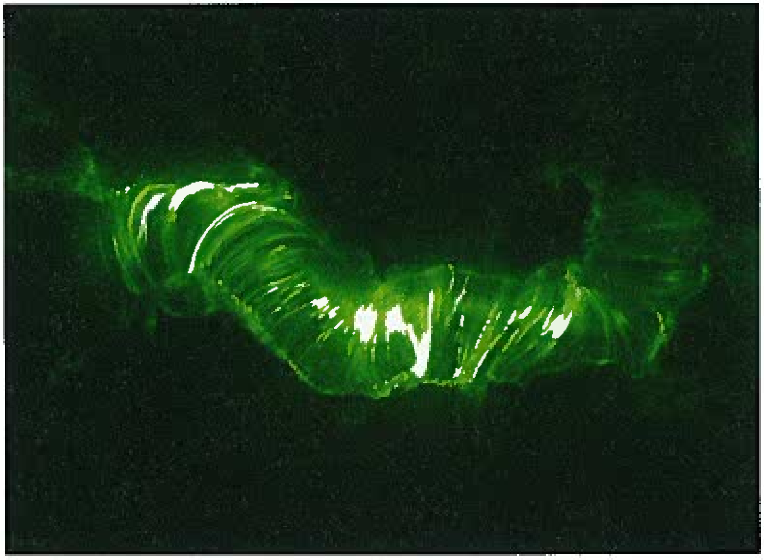

Figure 7: An arcade of post-flare loops imaged by the Transition Region And Coronal Explorer (TRACE) in the Fe XII 195 Å line.

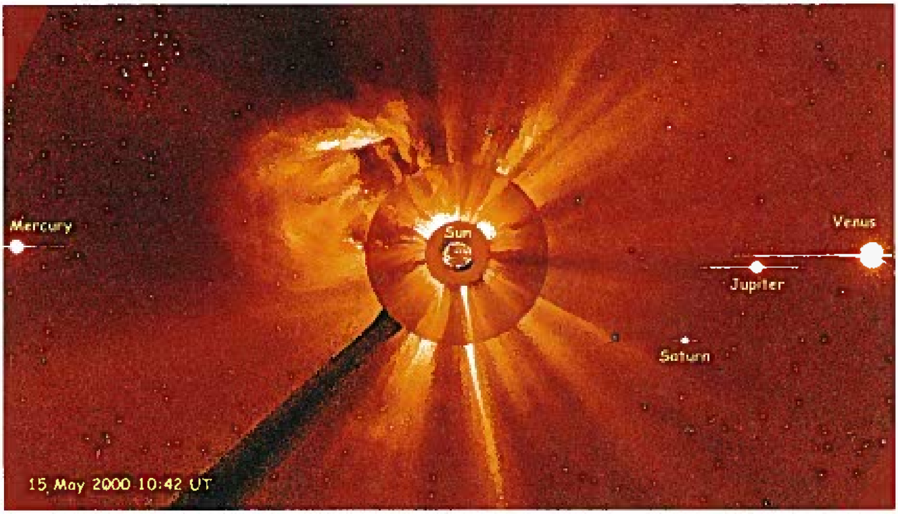

Figure 8: Composite of the Sun (centre, recorded by the EIT instrument on SOHO) and its surrounding corona recorded by the LASCO C2 and C3 coronagraphs on SOHO. Four solar system planets are visible in the image (marked), as well as stars of the Milky Way in the background (including the Pleiades in the upper left corner). On the upper left side of the Sun, a coronal mass ejection is in progress. Composite image kindly provided by B. Podlipnik.

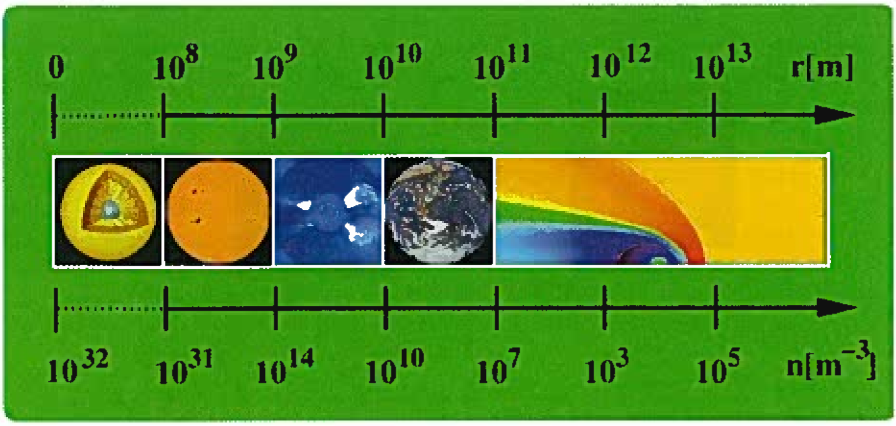

Figure 9: Illustration of the particle density in the Sun and in the Heliosphere. From Kneer et al. (2003).

The global strategy for observing the Sun from space is sketched in Figs. 10 and 11. In Fig. 10 the goals to be reached by the flotilla of currently flying and planned missions are outlined, with the types of goals to be addressed being associated with particular orbits. In this sense, solar physics is a research field at the interface of astrophysics and solar-system science, in that most observations are carried out remotely, but one can also fly to or around the object of study.

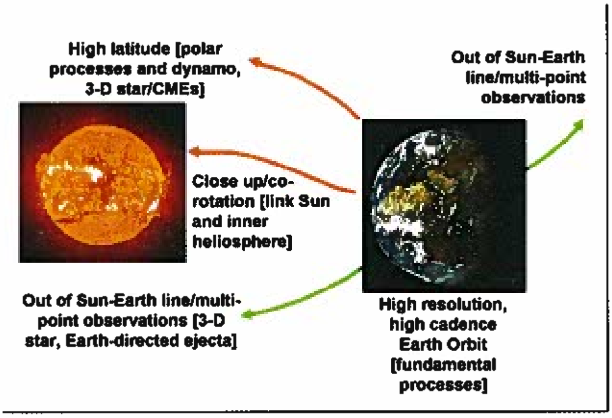

Figure 10: Illustration of the global strategy for solar observations, emphasizing the goals and the types of orbits that spacecraft need to take to achieve them. This figure builds upon an image in a presentation of R. Marsden.

The different orbital slots (Earth-orbit, studies from outside the Sun-Earth line, close-up orbits and solar polar views) are each associated with particular science goals. Thus when being inserted in Earth orbit, due to the ability to fly large instru-

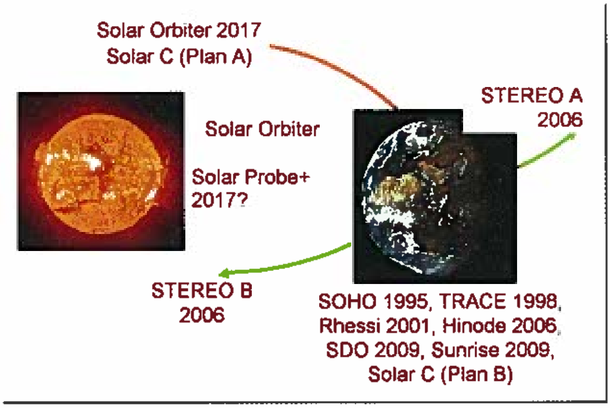

Figure 11: Illustration of the global strategy for solar observations, emphasizing the various current and planned solar space missions. By comparing with Fig. 10, it can be seen which general goals each of the missions follows. This figure builds upon an image in a presentation of R. Marsden.

ments there and the high data rate that can be achieved, spacecraft are particularly suited to aim at uncovering fundamental processes. Missions outside the Sun-Earth line are good for doing stereoscopy and for following disturbances (such as CMEs) from the Sun to the Earth. Going close to the Sun allows one to achieve high spatial resolution with relatively small instruments, and at the same time also enables one to sample the solar wind in situ, while it is still being accelerated. Finally, going outside the ecliptic provides a much clearer view of the poles and may also allow coronal loops and streamers to be studied from a novel viewpoint. Most solar space missions, which have flown so far or are flying currently, have been in orbits around the Earth or relatively close to Earth.

3 Current Missions

3.1 SOHO

The modern era of solar physics started with the SOlar and Heliospheric Observatory (SOHO), a cornerstone mission of ESA that was developed and operated jointly with NASA (Fleck et al. 1995; Domingo et al. 1995). The spacecraft, in a wide orbit around the Lagrangian L1 point, provides an uninterrupted view of the Sun and detects Earth-directed particles from the Sun before they can reach the Earth (due to the much smaller mass of the Earth, SOHO is 100 times closer to the Earth than to the Sun). SOHO was launched in 1995 and has been the workshorse of space-based solar physics since then, with a break in 1998, when contact with the spacecraft was lost for a number of months. Due to the untiring efforts of the ground-staff, SOHO was recovered against all odds.

SOHO harbours a set of 12 complementary science instruments, of which 8 are optical instruments and 4 detect particles and fields. The instruments allow the Sun to be probed from its core (via helioseismology), through the surface (via magnetograms) to the corona (via imaging and spectroscopy in the EUV as well as coronagraphy) and beyond into the Heliosphere (via coronagraphy and in situ measurements of particles). After 13 years in orbit SOHO is still going strong and providing valuable observations, although some of the instruments are now, or will soon be, outdone by more recent ones. Some of the main instruments onboard SOHO are:

- CDS (Coronal Diagnostic Spectrometer, Harrison et al. 1995) is an EUV spectrometer that mainly probes plasma at coronal temperatures but also provides information on the transition region.

- EIT (Extreme ultraviolet Imaging Telescope, Delaboudinière et al. 1995) produces full-disk images of the Sun in 4 wavelength bands (He II 304 Å, Fe IX 171 Å, Fe XII 195 Å, Fe XV 284 Å), sampling the solar atmosphere at different temperatures ranging from the upper chromosphere to the hot active-region corona.

- LASCO (Large Angle and Spectrometric COronagraph, Brueckner et al. 1995) is a suite of 3 coronagraphs that together cover the corona radially from 1.1 solar radii to 30 solar radii.

- MDI (Michelson Doppler Imager, Scherrer et al. 1995) provides velocity measurements over the solar disk, allowing the solar interior to be probed via helioseismology, as well as magnetograms of the full solar disk, which reveal the magnetic field at the solar surface.

- SUMER (Solar Ultraviolet Measurements of Emitted Radiation, Wilhelm et al. 1995), is a high-spatial and high-spectral resolution spectrograph covering the far ultraviolet (FUV) range. SUMER measures temperatures between 4000 K and 8 MK, i.e., it can diagnose the state of the plasma in the solar chromosphere, transition region and corona (including in flares).

- UVCS (UltraViolet Coronagraph Spectrometer, Kohl et al. 1995) measures the spectrum of the corona outside the solar limb (principle lines are Ly α, the O VI doublet and Mg X).

- VIRGO (Variability of Solar Irradiance and Gravity Oscillations, Fröhlich et al. 1995) measures the Sun's total irradiance, i.e., the total power radiated by the Sun in the direction of the Earth on time-scales of a minute to the solar cycle.

Fig. 8 has been put together from different images recorded by SOHO. A spectrum recorded by the SUMER spectrometer (Solar Ultraviolet Measurements of Emitted Radiation) onboard SOHO is displayed in Fig. 12. It corresponds to the spectrum of a very small part (1" $\times$ 1") of the Sun. The strongest line in the solar spectrum, the Lyα line, is marked.

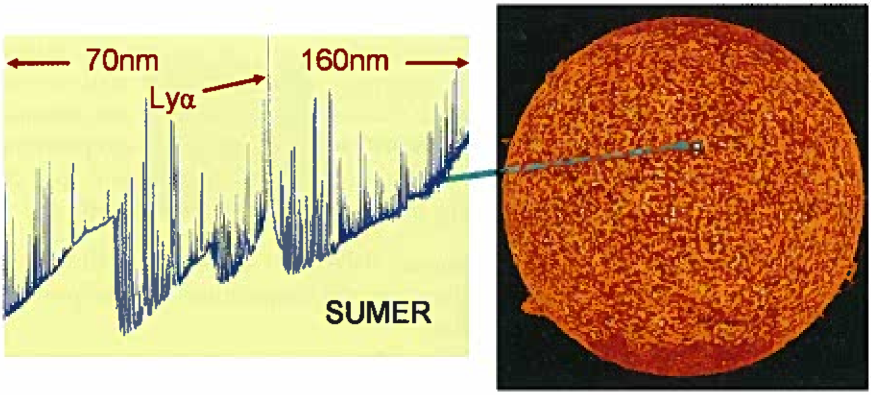

Figure 12: Left: Spectrum over the full spectral range covered by the SUMER instrument (onboard SOHO) in first spectral order displaying a plentitude of emission lines overlying different recombination continua. Right: Image of the full solar disk in a single spectral line (He I 584 Å) obtained by rastering the SUMER slit across the Sun. The arrow points to a box indicating that the spectrum shown in the left panel corresponds to only a small part of the solar disk.

3.2 TRACE and RHESSI

SOHO was followed by two smaller, highly dedicated, and also highly successful SMEX (SMall EXplorer) missions of NASA, the Transition Region And Coronal Explorer (TRACE) and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). They have very different aims. Whereas TRACE specializes in imaging at the highest spatial resolution achievable in the FUV (for solar observations from spacecraft), with the aim of getting a better handle on some of the open questions associated with coronal heating and in particular dynamics, RHESSI is aimed more at the most energetic events in the solar atmosphere, the flares.

TRACE explores the magnetic field in the solar atmosphere by studying its 3-D structure and temporal evolution in response to the photospheric flows, and investigates the time-dependent coronal fine structure and thermal topology. For this purpose, TRACE (Handy et al. 1998) is a pure imaging instrument, observing the Sun at 4 wavelengths (Fe IX 171 Å, C IV 1550 Å, Fe XII 195 Å, and the continuum at 1700 Å). It was launched on a Pegasus rocket in April 1998. The launch was scheduled to allow joint observations with SOHO during the rising phase of the solar activity cycle.

The TRACE telescope has a 30-cm aperture and primary and secondary mirrors that are segmented into quadrants. Each quadrant has a different normal-incidence coating for the EUV and UV. The segmented coatings on the mirrors form identically sized and coaligned images (which can be observed one after the other). It observes plasmas at selected temperatures from 6000 K to 10 MK, with a typical temporal resolution of less than one minute and a spatial resolution of 1", given by a pixel size of 0.5". A detector with 1024 × 1024 pixels allows a field of view of 8.5 × 8.5 arcminutes squared to be covered. TRACE is located in a sun-synchronous polar orbit in order to minimize interruptions to the observations.

RHESSI (Lin et al. 2002) is also a SMEX mission flying in a nearly circular, 38° inclination, 600-km altitude orbit. It was launched on 5 February 2002. RHESSI is designed to investigate particle acceleration and energy release in solar flares. It does this through a combination of imaging and spectroscopy of hard X-ray/gamma-ray continua emitted by energetic electrons, and of gamma-ray lines produced by energetic ions. RHESSI has a single science instrument that consists of an imager, made up of nine bi-grid rotating modulation collimators (RMCs), in front of a spectrometer with nine cryogenically-cooled germanium detectors (GeDs), one behind each RMC. The spatial resolution can be as high as $\approx$ 2.3 arcsec, and the field of view covers the full Sun (1°). The spectral resolution ranges from 1 to 10 keV between soft X rays (3 keV) and gamma rays (17 MeV).

3.3 Hinode

The Hinode mission (Kosugi et al. 2007) aims to understand how magnetic energy gets built up in the photosphere and how it is explosively released in the upper atmosphere. The Hinode satellite (formerly Solar-B) of the Institute of Space and Astronautical Science (ISAS) belonging to the Japan Aerospace Exploration Agency (JAXA) was launched in September 2006. Hinode carries three instruments: the Solar Optical Telescope (SOT, Tsuneta et al. 2007), the EUV Imaging Spectrometer (EIS, Culhane et al. 2007), and the X-Ray Telescope (XRT, Golub et al. 2007).

The Solar Optical Telescope (SOT) is the largest instrument onboard Hinode. It consists of a 50-cm Gregorian telescope (the Optical Telescope Assembly, or OTA) and the Focal Plane Package (FPP). The OTA provides diffraction-limited images at a resolution (2 pixels) between 0.2 and 0.3 arcsec (depending on the wavelength). The FPP includes the Narrow-band Filtergraph Imager (NFI), the Broad-band Filtergraph Imager (BFI) and the Spectro-Polarimeter (SP). The NFI was designed to provide full Stokes profiles at a variety of wavelengths, but was finally limited to a restricted number of wavelengths due to a technical problem discovered in flight, while the BFI images the Sun in 6 roughly 0.3-1 nm wide bands (CN-band at 388 nm, Ca H core, G-band at 430 nm, blue continuum at 450 nm, green continuum at 555 nm and red continuum at 668 nm). Finally, the SP provides full Stokes profiles in the Fe I 6302.5 Å (Landé $g = 3$) and Fe I 6301.5 Å ($g_{\text{eff}} = 1.67$), allowing the full magnetic vector to be determined at a resolution of 0.3 arcsec.

The X-Ray Telescope (XRT) is a high-resolution grazing incidence telescope with the primary purpose to observe the generation, transport, and emergence of solar magnetic fields, as well as the ultimate dissipation of magnetic energy in flare emission, coronal heating, and coronal mass ejections. XRT provides coronal images at different temperatures, with a partial-disk and a full-disk field of view (FOV), which is larger than 30 arcminutes. One of the unique features of XRT is its wide temperature coverage: $6.1 < \log (T/K) < 7.5$. The XRT consists of the X-ray and visible-light optics, focal plane mechanisms, and the 2k × 2k CCD camera. The angular resolution is 2 arcminutes squared, the temporal cadence is 2 s (at reduced FOV), and the exposure time ranges from 4 ms to 10 s.

EIS is a normal-incidence multi-layer coated EUV spectrometer that observes coronal and upper transition-region emission lines between 170 and 210 Å and between 250 and 290 Å. EIS has a pixel size corresponding to 1 arcsec in the spatial and 25 km s^{-1} in the spectral direction. It can scan a field of 6 × 8.5 arcminutes, with a typical exposure time of 2-5 s in active regions. It aims to characterize various physical parameters in the solar corona including in solar flares. These parameters include plasma bulk flow and turbulent velocities, the local plasma temperatures and densities, the differential emission measure and element abundances.

3.4 STEREO

The STEREO mission is composed of two spacecraft roughly following the Earth's orbit. One of these is lagging behind, the other moving ahead of the Earth. STEREO is a mission driven basically by the need to better understand the causes of space-weather. STEREO's scientific objectives are to:

- Understand the causes and mechanisms of coronal mass ejection (CME) initiation,
- Characterize the propagation of CMEs through the heliosphere,
- Discover the mechanisms and sites of energetic particle acceleration in the low corona and the interplanetary medium,
- Improve the determination of the structure of the ambient solar wind.

With its two spacecraft STEREO provides a novel view of the Sun and of the heliosphere between Sun and Earth. Together, the spacecraft provide 3-D views of solar coronal features, such as loops, plumes and coronal mass ejections and trace the flow of energy and matter from the Sun to Earth.

Both spacecraft carry identical instrumentation, composed of an optical instrument suite, SECCHI (Sun Earth Connection Coronal and Heliospheric Investigation), an interplanetary radio burst tracker (SWAVES or STEREO/Waves), an energetic particles and fields package IMPACT (In-situ Measurements of Particles And CME Transients) and a plasma package PLASTIC (PLasma And Supra-Thermal Ion Composition). SECCHI (Howard et al. 2008) is itself composed of a set of instruments:

- SECCHI EUVI (Extreme UltraViolet Imager, Wuelser et al. 2007) is a set of telescopes that images the full solar disk out to 1.7 solar radii at 4 EUV wavelengths (He II 304 Å, Fe IX 171 Å, Fe XII 195 Å, and Fe XV 284 Å, i.e., the same wavelengths as recorded by EIT) with 2048 × 2048 pixel detectors (1.6 arcsec per pixel)
- SECCHI COR1 is the inner coronagraph (Thompson et al. 2003), a classic Lyot internally occulted refractive coronagraph with a field of view from 1.3 to 4 solar radii.

- SECCHI COR2 is the outer coronagraph that images the corona between 2 and 15 solar radii. Like COR1, COR2 also studies the corona in polarized light (K corona).
- SECCHI HI (Heliospheric Imager) is an externally occulted coronagraph with an extremely wide field of view, covering the heliosphere from the Sun to the Earth (12-318 solar radii). HI follows coronal mass ejections in interplanetary space by direct imaging.

IMPACT measures the plasma characteristics of local solar energetic particles (sampling their 3-D distribution functions) and the local vector magnetic field. SWAVES traces the generation and evolution of traveling radio disturbances from the Sun to the orbit of Earth (i.e., the orbit of the STEREO spacecraft). The aim of PLASTIC is to provide plasma characteristics of protons, alpha particles and heavy ions (determining the form of their mass and charge state composition).

4 Future Missions

In the following we briefly describe in some detail the main solar space missions that are being built, designed, or planned for the future.

4.1 Sunrise

We start with a project that is not strictly a space mission, but qualifies to be included here, since it is funded and run by space agencies and has many similarities with space missions. The Sunrise project (Barthol et al. 2008) aims to fly a solar observatory to study the Sun at a spatial resolution reaching 0.05 arcsec on a stratospheric balloon. The main aim of this project is to investigate magnetoconvection, i.e. the interaction between the magnetic field and convection, which dominates the dynamics of the magnetic field in the subsurface layers and the lower atmosphere of the Sun and loads the field with the excess energy that is later released through energetic events in the corona. As such, the goals of Sunrise are similar to those of the SOT on Hinode, but Sunrise aims to achieve an up to four times higher spatial resolution and to observe different spectral bands.

A 1-m diameter, diffraction limited telescope feeds light simultaneously into two science instruments, a broad-band imager (SUFI - SUnrise Filter Imager) that covers the wavelength range from 220 nm to the CN-band at 388 nm and an imaging vector polarimeter (IMAX - Imaging MAgnetograph eXperiment) that will provide the full vector magnetic field in a Zeeman-sensitive photospheric line (Fe I 5250.2 Å).

The first science flight is scheduled for the summer of 2009 from the European ballooning facility, ESRANGE, in northern Sweden. At that time of year at this latitude (close to the arctic circle) steady winds in the stratosphere are expected to carry the balloon and its payload across the Atlantic to northern Canada, where it is expected to land. Also, at the float altitude of above 30 km the payload is expected to receive uninterrupted sunlight throughout the flight.

4.2 Solar Dynamics Observatory

The Solar Dynamics Observatory (SDO) is the cornerstone of NASA's Living with a Star program, with a currently scheduled launch in October 2009. The spacecraft will fly in a geostationary orbit, chosen such that it simultaneously allows for uninterrupted solar viewing and for high data downlink to a dedicated antenna. SDO carries three science instruments.

HMI (Helioseismic and Magnetic Imager) is a dual-purpose instrument, providing two main data sets. The first of these is composed of helioseismic data (velocities measured over the whole solar disk) to probe the solar interior. The second data set is composed of magnetic field measurements that probe the solar surface layers. HMI will extend the capabilities of the SOHO/MDI instrument with continuous full-disk coverage at higher spatial resolution and extend the magnetic field measurements from longitudinal to vector magnetic fields.

The AIA (Atmospheric Imaging Assembly) instrument is composed of an array of telescopes that will image the solar atmosphere in 10 wavelengths (7 in the EUV, 2 in the FUV and 1 in the visible) every 10 s. These channels, which include a white-light channel, continuum at 1700 Å, He II 304 Å, C IV 1550 Å, Fe IX 171 Å, Fe XII, XXIV 193 Å, Fe XIV 211 Å, Fe XVI 335 Å, Fe XVIII 94 Å, Fe VII, XX, XXIII 131 Å, will cover a wide range of temperatures (log (T/K) ranging from 3.7 to 7.3).

EVE (Extreme-Ultraviolet Variablity Experiment) will measure the solar extreme-ultraviolet (EUV) irradiance at high spectral resolution, temporal cadence, and precision.

4.3 Solar Orbiter

The Sun's atmosphere and the heliosphere represent uniquely accessible domains of space, where fundamental physical processes common to solar, laboratory and astrophysical plasmas can be studied in detail impossible on Earth or from astronomical distances. Results from past missions such as Helios, Ulysses, Yohkoh, SOHO and TRACE have advanced our understanding of the Sun and its corona and associated solar wind, as well as the three-dimensional heliosphere enormously. However, we have reached the point where further in situ measurements, now much closer to the Sun, together with high-resolution imaging and spectroscopy from a near-Sun and out-of-ecliptic perspective, promise to bring about major science breakthroughs.

The Solar Orbiter mission (Marsch et al., 2005) will do exactly this. It is one prominent candidate (with possible launch in 2017) of ESA's future Cosmic Vision (CV) science programme and will be the first spacecraft to approach much closer to the Sun than planet Mercury. Its novel orbital design will allow Solar Orbiter to achieve the following unique aims. It will

- explore the uncharted innermost regions of our solar system,
- study the Sun from close-up (48 R_S or 0.22 AU),
- fly by the Sun and examine its surface and the space above from a nearly co-rotating vantage point,

- provide images of the Sun's polar regions from heliographic latitudes as high as 35°.

The science definition team for Solar Orbiter had the task of defining the scientific goals of the mission, prioritizing them in order to achieve a well-balanced and highly focused mission, and finally identifying the measurements needed to achieve them. The thus defined four main scientific goals of the mission can be stated as follows. Solar Orbiter will

- determine the properties, dynamics and interactions of plasma, fields and particles in the near-Sun heliosphere,
- investigate the links between the solar surface, corona and inner heliosphere,
- explore, at all latitudes, the energetics, dynamics and fine-scale structure of the Sun's magnetized atmosphere,
- probe the solar dynamo by observing the Sun's high latitude field, flows and seismic waves.

Due to its proximity to the Sun, Solar Orbiter will be able to resolve such important scales as the photon mean free path, the barometric scale height and a flux tube diameter in the photosphere (about 150 km). In comparison with SOHO/EIT and the TRACE imagers, Solar Orbiter instruments will improve the spatial resolution by a factor of 5 to 10. The typical pixel size is 1850 km for SOHO, 350 km for TRACE, and will be 75 km for the imagers on Solar Orbiter. It will allow us to study the magnetic structure and evolution of the polar regions, the detailed flow patterns in the polar regions and development of magnetic structures by using local-area helioseismology at heliographic latitudes of up to 35°. The science questions and specific aims are summarized in the Science Requirements Document, original Assessment Study Report, and the paper by Marsch et al. (2005), which contains the relevant references.

The present spacecraft design foresees a three-axis-stabilized spacecraft. Critical design issues are the expected maximal heat load of up to 27 kWm^{-2}, equivalent to 20 solar constants at Earth, the variable radiation environment that affects detector electronics, and the coatings and filters of optical instruments. The limited spacecraft resources put tight constraints on the available mass and power, and on the telemetry rate. In order to meet all these challenges, it was necessary to develop low-resource instrumentation, identify and initiate new technology developments, and study critical payload and spacecraft aspects as early as possible. To these ends a payload working group, made up of members of the scientific community with expertise in the kind of instrumentation envisaged for Solar Orbiter, studied the crucial questions related to the proposed instruments, and came up with possible solutions for all of the critical problems and design issues.

After considerable discussion, the optimized Solar Orbiter payload addressing best, within the available resources, the key science goals of the mission encompasses the following instrumentation: The in-situ suite of instruments for heliospheric measurements consists of a plasma package, fields package, and particles package; the comprehensive remote-sensing suite for solar observations consists of a visible-light polarimetric imager, an ultraviolet spectrometer and an ultraviolet multi-telescope imager, a coronagraph, a spectrometer/telescope imaging X-rays, and finally a heliospheric imager that takes pictures of the entire inner heliosphere.

The Solar Orbiter will achieve its wide-ranging aims with this set of sophisticated instruments. The baseline payload presently has a total mass of about 170 kg, a power consumption of 170 W, and a telemetry rate of about 90 kbs. The Announcement of Opportunity to propose for this payload was released by ESA and NASA in September of 2008. The selection of instruments is expected to be announced in March 2009. The downselection of the first medium class mission for CV will then take place in the autumn of 2009.

4.4 Solar Probe Plus

The current study of a solar probe is in line with old studies, dating back to a report of the Space Science Board of the US National Academy of Sciences from October 1958. However, half a century later, in situ observations from a solar probe have still not been made, and yet they are required to understand fully coronal heating and solar wind acceleration. The science goals of the Solar Probe Plus, with a lowest perihelion of 10 R_S, are to

- determine the structure and dynamics of the magnetic fields at the sources of the fast and slow solar wind,
- trace the flow of energy that heats the corona and accelerates the solar wind,
- determine what mechanisms accelerate and transport energetic particles,
- explore dusty plasma phenomena in the near-Sun environment and their influence on the solar wind and energetic particle formation.

The science implementation will include a statistical survey of the outer corona, with the spacecraft staying for about 1000 hours inside 20 R_S and thus provide excellent sampling of all types of solar wind, and promises more time within the Alfvén critical point than previous studies. Complete in-situ measurements of thermal plasma ions and electrons, suprathermal particles, energetic particles, magnetic fields, waves, neutrons, and dust will be made. The additional on-board remote-sensing observations by a hemispheric white-light imager will provide the local context for the in-situ measurements. Coordinated remote-sensing from other assets will provide views of the solar source regions for the about 500 hours while Solar Probe Plus is inside 20 R_S. A participating scientist programme and extensive theory and modeling efforts will accompany the mission. An announcement of opportunity is expected to be issued by NASA in the spring of 2009.

4.5 Solar-C

Solar-C is the next japanese solar mission and is now in the early planning stage. There are two different scenarios for the mission, namely, a polar-observing mission ("Plan A") and a high-resolution spectro-polarimetry mission targeting the photosphere-chromosphere-transition region-corona coupling ("Plan B"). Although many of the details of this mission have not yet been worked out, some aspects can already be mentioned.

For Plan A the current aim is to reach an orbit with a maximum heliographic latitude of approximately 45° at a distance of roughly 1 AU. From there the global structure of the magnetic field and the corona are to be studied using small optical instruments. The questions to be addressed are similar to those to be addressed by Solar Orbiter in its extended mission phase (high-latitude phase). The difference is that the orbit of Solar-C will be optimized towards such high-latitude observations. Thus the spacecraft will spend longer consecutive periods at high latitudes than Solar Orbiter, and reach somewhat higher heliographic latitudes (45° compared to 35°). This has some advantages for helioseismology of the polar regions.

For Plan B a similar optical telescope is currently envisaged as now flying with Hinode. However, in addition to sampling the photospheric field and dynamics, the emphasis will be placed on magnetic fields in and dynamics of the solar chromosphere. The main science aim is to study the transport of the energy from the photosphere to the corona through the chromosphere and the transition region.

The orbit options for the Plan A spacecraft include performing the orbit maneuver with large ion engines, or using Jupiter and Earth swing-bys (in some ways similar to Ulysses, although a shorter orbit not reaching such high latitudes is envisaged).

5 Summary

The Sun provides a rich source of information that is of wide interest, influencing our understanding of the physics underlying the phenomena in many branches of astrophysics and well beyond that. To uncover the answers to the many open questions that the Sun poses, a little flotilla of spacecraft is currently active. The most important among these were briefly described in this article.

However, we stress that this list is not complete. There are a number of others, for example the two solar wind monitoring spacecraft ACE and WIND (each probing different science aspects), or the solar irradiance measuring mission, SORCE, which were not covered here. We have also not discussed any missions here that are no longer delivering data. These include the Skylab manned observatory, the series of Orbiting Solar Observatories (OSO), the Solar Maximum Mission (SMM), the Helios, Ulysses and Yohkoh spacecraft and many more.

The future looks bright for solar space projects, in particular in the US, Japan, China and India. There are a number of projects at different stages of planning and funding in these countries, such as the Solar Probe Plus, the Solar Sentinals, the IRIS spectrometer in the USA, the Kuafu and Space Solar Telescope missions in China, Solar-C in Japan, a coronagraph mission in India, to name but a few.

In Europe, the very strong and successful solar community (SOHO is, with the exception of the HST, the most productive ESA mission, having so far produced the largest number of scientific papers) is still waiting for the Solar Orbiter mission to be confirmed by ESA. Although it was initially selected in 2000 for a launch in

2007, it will not be launched before 2017, being now a part of the Cosmic Vision programme. Admittedly, technology developments for the future, with the PROBA-2 and probably the PROBA-3 missions carrying solar payloads, are important, but are in no way a replacement for a dedicated solar mission.

Acknowledgements

We thank T.J. Okamoto, B. Podlipnik, M. Carlsson, V. Zakharov, J. Hirzberger, R. Marsden, and T. Riethmueller for providing material.

References

Barthol, P., Gandorfer, A. M., Solanki, S. K. et al. 2008, Adv. Space Res. 42, 70-77

Brueckner, G. E., Howard, R. A., Koomen, M. J., et al. 1995, Solar Phys. 162, 357

Camp, C. D., Tung K. K. 2007, GRL, 34, L14703, doi:10.1029/2007GL030207,

Culhane, J. L., Harra, L. K., James, A. M. et al. 2007, Solar Phys. 243, 19

Delaboudinière, J.-P., Artzner, G. E., Brunaud, J., et al. 1995, Solar Phys. 162, 291

Domingo, V., Fleck, B.,& Poland, A. I. 1995, Solar Phys., 162, 1

Fleck, B., Domingo, V., & Poland, A. I. (Eds.) 1995, Solar Phys., Vol. 162

Fröhlich, C., Romero, J., Roth, H., et al. 1995, Solar Phys. 162, 101

Golub, L., Deluca, E., Austin, G. et al. 2007, Solar Phys., 243, 63

Harrison, R. A., Sawyer, E. C., Carter, M. K., et al. 1995, Solar Phys. 162, 233-290

Howard, R. A., Moses, J. D., Vourlidas, A. et al. 2008, Space Sci. Rev., 136, 67-115

Kneer, F., Solanki, S.K., Strassmeier, K.G., von der Lühe, O., Wimmer-Schweingruber, R.P. 2003, Perspektiven der Erforschung der Sonne und Heliosphäre in Deutschland, Copernicus-Verlag, Katlenburg-Lindau

Kohl, J. L., Esser, R., Gardner, L. D., et al. 1995, Solar Phys. 162, 313

Kosugi, T., Matsuzaki, K., Sakao, T., et al. 2007, Solar Phys., 243, 3

Lin, R. P., Dennis, B. R.; Hurford, G. J. et al. 2002, Solar Phys., 210, 3

Marsch, E., Marsden, R., Harrison, R., Wimmer-Schweingruber, R., and Fleck, B. 2005 Adv. Space Res., 36, 1360

Okamoto, T. J., et al. 2007, Science, 318, 1577

Scherrer, P. H., Bogart, R. S., Bush, R. I., et al. 1995, Solar Phys. 162, 129

Thompson, W. T., Davila, J. M., Fisher, R. R. et al. 2003, Proc. SPIE, 4853, 1-11

Tsuneta, S., Ichimoto, K., Katsukawa, Y. et al. 2008, Solar Phys., 249, 167

Wilhelm, K., Curdt, W., Marsch, E., et al. 1995, Solar Phys. 162, 189

Wülser, J.-P., Lemen, J. R., Tarbell, T. D. et al. 2007, Proc. SPIE, 5171, 111