Mem. S.A.It. Vol. 84, 286

Memorie della

European Solar Physics: moving from SOHO to Solar Orbiter and beyond

S.K. Solanki[1,2], L. Teriaca[1], P. Barthol[1], W. Curdt[1], and B. Inhester[1]

[1] Max Planck Institute for Solar System Research – Max-Planck-Str. 2, 37191 Katlenburg-Lindau, Germany
[2] School of Space Research, Kyung Hee University, Yongin, Gyeonggi, Republic of Korea
e-mail: solanki@mps.mpg.de

Abstract. When ESA and NASA launched the Solar and Heliospheric Observatory (SOHO) to the Sun-Earth L1 point, they also launched European solar physics into a steep upward trajectory. Thanks to the battery of instruments on SOHO our picture of the Sun changed dramatically from that of a sedate, nearly static star into that of a highly structured, dynamic one. Subsequent solar missions have probed higher energy radiation, gazed at the Sun from new vantage points in the ecliptic, analysed the Sun at higher spatial resolution and imaged the whole Sun in many wavelengths at high cadence. Nonetheless, SOHO is still going strong and still delivering unique data. In the meantime European solar physicists are working hard on the next major mission, Solar Orbiter, now being implemented as the M1 mission of ESA's Cosmic Vision program. Solar Orbiter will leave the Earth's orbit and move ever closer to the Sun, reaching a perihelion inside the orbit of Mercury. This will allow it to sample the Sun's dynamic inner heliosphere in situ, while probing the source regions of the ambient solar wind with its remote sensing instruments, a unique combination. Solar Orbiter will also leave the ecliptic and, for the first time, image the Sun's poles. This will bring us closer to finding the missing pieces of the puzzle on how the solar dynamo works. Beyond Solar Orbiter are further exciting prospects, such as the Solar-C mission, or the large European Solar Telescope. Here an overview of solar missions and telescopes and the associated science is given from a European perspective.

Key words. Sun – Heliosphere – Instrumentation – Space Missions

1. Introduction

Our Sun – supplying Earth with warmth and light – is the only star that can be observed with a spatial resolution good enough to provide prototypical information of astrophysical processes in the universe. But even under such favourable conditions, our understanding of solar phenomena is limited and today's knowledge can only be the starting point for a deeper investigation. Not only can we resolve features on the Sun, but we can also fly into its outermost atmosphere (the heliosphere) and sample the gas there, determining its elemental and isotopic constituents, directly measuring the turbulence there, etc. It is consequently not surprising that the Sun has often been called the Rosetta stone of astrophysics.

Send offprint requests to: S.K. Solanki

The key player in processes from the solar interior into the heliosphere is the magnetic field. Its complex interactions with turbulent convection, differential rotation, oscillations, waves and radiation give rise to the rich tapestry of phenomena and processes that together make up solar activity, which in turn is of interest not only for astrophysics, but is also of direct relevance to our natural and technical environment on Earth. However, these interactions are often only poorly understood, so that observational constraints are extremely important: with few exceptions, most phenomena on the Sun have first been discovered observationally and have only later found a theoretical explanation.

We observe the Sun both from the ground and from space (where we can also directly sample the solar wind). Instruments in space can overcome the limitations exerted by the Earth's atmosphere, thus complementing ground-based observatories. Such limitations are not just in wavelength – radiation from some of the most interesting parts of the solar spectrum is absorbed in the Earth's atmosphere. To overcome this limitation has been the traditional reason for going to space for remote sensing. Other reasons that have been steadily gaining in importance are:

- to overcome the turbulence of the Earth's atmosphere in order to obtain time series of homogeneous high spatial resolution,
- to ensure long, uninterrupted time series of Doppler shift or intensity, as required for helioseismologic studies,
- to overcome brightness fluctuations introduced by the atmosphere (important for irradiance measurements, i.e. measurements of the Sun's global radiative flux),
- to observe the Sun from other vantage points, e.g. in order to be able to follow coronal mass ejections directed towards Earth,
- to directly detect particles coming from the Sun, which are stopped by the Earth's magnetosphere and atmosphere,
- to make in-situ measurements of heliospheric parameters, such as magnetic fields or waves.

An armada of highly successful space missions has been launched and operated worldwide in the last decades, each of which has pressed one or the other of the above advantages (and often many of them together). And more solar space missions are being prepared or planned.

Ground-based solar physics has also been moving forward in parallel to the space-based efforts. The main advantages of observing from the ground are:

- comparatively low cost,
- instruments can be repaired, improved, even replaced without too much disruption (unlike for space-borne instrumentation),
- large telescopes can be built (at least for observations in the visible),
- sub-mm, mm-wave and longer wavelength dishes, otherwise used by astronomers to investigate non-solar objects, can also be employed to study the Sun.

A third group of instruments are those carried into the stratosphere by giant balloons. These share some of the advantages of both groups.

- They fly above a sufficient amount of the atmosphere to provide virtually seeing-free observations.
- They have access to wavelengths as short as 200 nm.
- The instruments and infrastructure can be improved or replaced from one flight to the next.
- They cost much less than space missions.

The major disadvantage of balloon-borne instruments is that the flights are relatively short (generally less than 2 weeks), so that only a limited amount of data can be gathered per flight.

Thus observatories of all these types, space-borne, ground-based and balloon-borne are playing an important role in answering the major open questions facing solar physicists. The need to resolve the Sun better, to observe it from new perspectives and to probe its wind at a range of distances from the Sun requires a new generation of observatories and instruments, some of which, along with the currently operating ones, are introduced below, always from a European point of view.

In the following we first give a very brief introduction to the exciting science of the Sun, in Sect. 2. Then, in Sects. 3 and 4, we provide an overview of currently active solar space (and balloon-borne) missions led by Europe, or with a significant European involvement, along with some of the science highlights achieved by them. In Sect. 5 future space missions of importance for the European solar community are described, in particular Solar Orbiter and Solar-C. Both current and future European ground-based solar telescopes are introduced in Sect. 6. A summary is given in Sect. 7.

2. The Sun: our exciting star

Our Sun is an important star for mainly two reasons. Firstly, it is a unique physical system that helps us to understand other astronomical objects, secondly it is our star that creates a habitable setting on Earth, but also influences our natural and technical environments through its activity. The Sun supplies the Earth with the power needed to maintain it at temperatures at which water is liquid and with the light required by many of the chemical reactions taking place in nature. Without the radiation from the Sun human life would not be possible. Hence the Sun is truly our life-giving star.

In spite of the great progress made in resolving stellar surfaces by techniques such as interferometry, Doppler imaging, or eclipse/transit mapping, the Sun remains the only star whose surface we can resolve on scales down to 100 km. We can resolve structures and follow the evolution of phenomena that give us insight into the basic physical processes acting not only on the Sun, but in a variety of other astronomical objects (and other physical systems as well). Thus the Sun is prototypical of other cool stars and the convection, magnetic activity and atmospheric and internal structure that they possess, but also allows us to study processes that are expected to take place in, e.g., accretion disks as well. The Sun is also a giant plasma-physics laboratory and has contributed to major advances in atomic, nuclear and particle physics (the latter through, e.g., the neutrino problem and its resolution).

At the spatial resolution that is now achievable the Sun has revealed to us a rich variety of structures and phenomena that include granules and supergranules, convection cells that transport the energy flux to the solar surface which feeds the Sun's radiative losses, as well as small magnetic elements, or spicules (material ejected from near the solar surface into the corona). In addition, the substructure of larger features, such as sunspots, which are composed of penumbral filaments, i.e. elongated bright structures pervading the penumbra, and umbral dots, i.e. compact bright features in the dark umbrae of sunspots, is only now beginning to be properly resolved. The important point here is that the properties and spatial distribution of these small features, each less than a hundredth of the sunspot's size, are now known to define the fundamental properties of their parent sunspots. Going higher in the atmosphere, coronal loops, which dominate and shape the million-degree corona are thought to be composed of strands with widths at the limit of the presently achievable spatial resolution. Waves that carry energy to heat the corona through the atmosphere are also coherent on rather small scales only. Observations of these and many more structure and phenomena, too numerous to list here, all suggest that although we have partly resolved them, much of the important detail driving the physics, may still be unresolved and would call for further, improved observations.

Figure 1 displays a sunspot reconstructed from data recorded by the Solar Optical Telescope Spectropolarimeter (SOT/SP) on the Hinode spacecraft. The 4 panels depict the continuum intensity (which looks similar to white-light intensity), the magnetic field strength, magnetic field inclination and the line of sight velocity, all deduced from a simultaneous inversion of all the observed Stokes profiles together by Tiwari et al. (in preparation), employing the technique of van Noort (2012), that strongly reduces the effects of the instrument's point spread function. The three last quantities are represented at unit continuum optical depth level ($\tau_{c,500} = 1$, i.e. at the solar surface, where

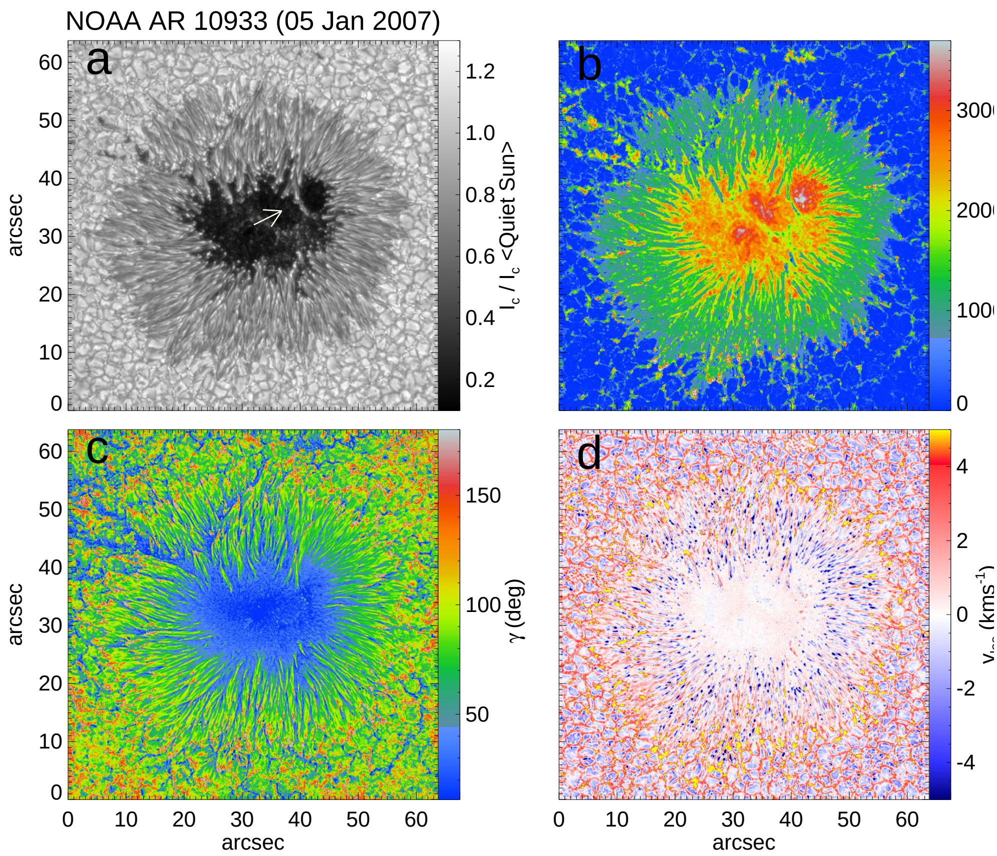

Fig. 1. Parameters of a sunspot deduced from inversions of observations recorded by the Spectropolarimeter on the Hinode spacecraft. The panels display (a) the reconstructed continuum intensity, (b) the magnetic field strength, (c) the magnetic field inclination and (d) the line-of-sight velocity. Figure kindly provided by S. Tiwari.

variations are the strongest and which show the convection taking place in a sunspot the best). The strong fine structure, present not just in the intensity image, but also in the images of the other physical parameters is typical of any large solar feature, which often show substantial sub-structures that are often crucial for determining the global properties of the feature as a whole. In the case of sunspots, the fine structure reflects magnetoconvective processes that are responsible for most of the energy transport from the solar interior to the surface. This form of convection, taking place in a strong and heavily inclined magnetic field produces very elongated convection cells (the penumbral filaments) which can be compared with the irregular, but hardly elongated granules, the convection cells seen around the sunspot in Fig. 1.

Sunspots are the largest magnetic features seen at the solar surface. At the other extreme are small magnetic elements that have only very recently been resolved (see Sect. 4.2). These appear as bright points in solar images and some can be seen in Fig. 11 described in Sect. 4.2.

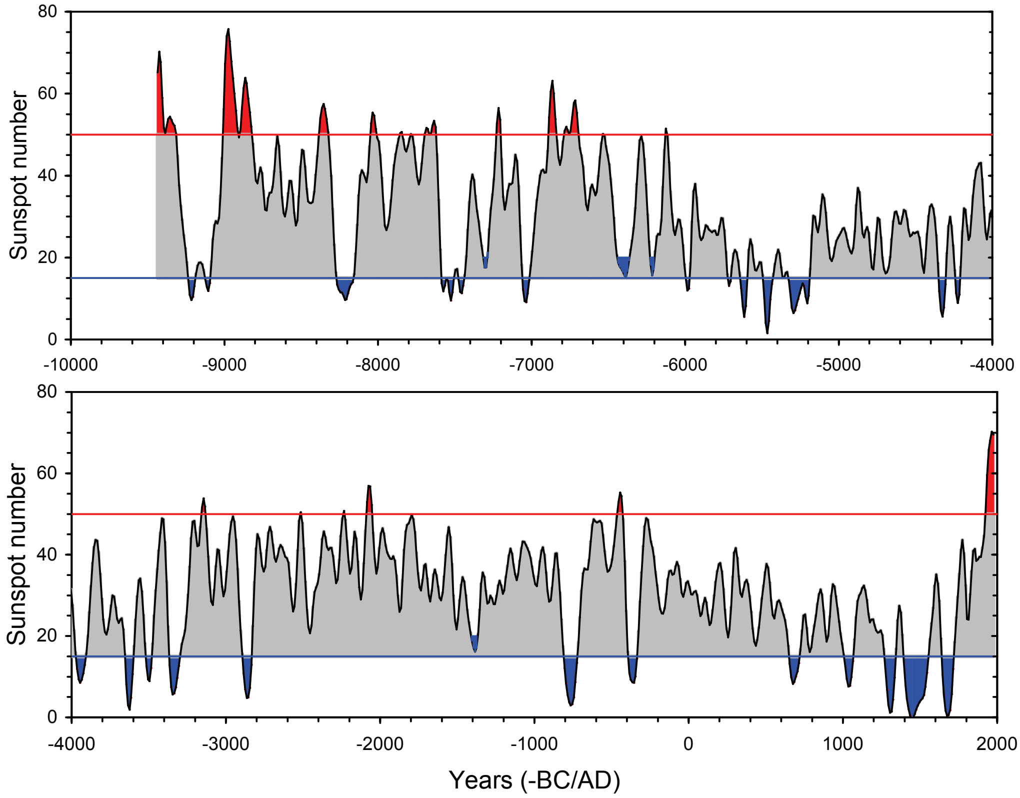

Fig. 2. Sunspot number reconstructed from the concentration of the cosmogenic isotope ^{14}C after applying a set of models. The smoothed data reach back approximately 11400 years. Periods of particularly low activity lasting at least 20 years are shaded blue, while periods of particularly high activity are marked in red. From Usoskin et al. (2007).

The number of dark sunspots and bright magnetic elements at the solar surface changes with time, according to the phase of the solar cycle, which is driven by a dynamo deep in the solar interior. However, this dynamo does not work at a constant rate, sometimes producing strong cycles, sometimes weak ones and sometimes failing to produce any clear cycle at all. A record of solar activity over the last 11000 years, i.e. over most of the holocene, is plotted in Fig. 2. Numerous periods of exceptionally low solar activity can be seen (the so-called grand minima, coloured blue in the figure), with the latest of these, the Maunder minimum, ending around the year 1700 after over 60 nearly spotless years. Times of extraordinary activity, the grand maxima, are marked in red (for more details see Usoskin et al. 2007). The most recent one is in the process of ending. It is unclear at what level solar activity will continue, as our capability to predict future activity is still quite limited.

The Sun occasionally also produces fireworks in the form of flares caused by the reconnection of magnetic field lines. Flares accelerate strong beams of energetic particles within seconds and release copious amounts of energetic radiation (UV and x-rays) within minutes. In addition, most flares are associated with coronal mass ejections (CMEs) that release millions of tons of coronal gas into the interplanetary medium (approximately half the energy released in a flare goes into accelerating the CME). An example of a CME, as seen by

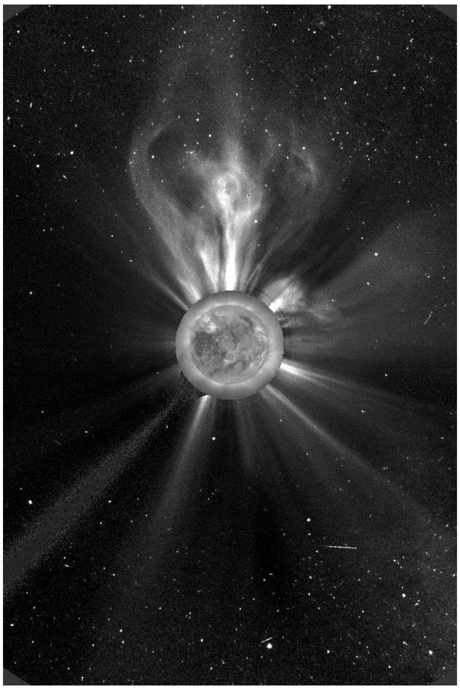

Fig. 3. A coronal mass ejection (CME) that occured close to the turn of the millenium observed by the LASCO coronagraph onboard SOHO. An image of the Sun recorded by EIT has been superimposed to fill the otherwise blank area covered by the occulting disk of the coronagraph. This solar image is not to scale, being somewhat larger than the actual size of the Sun compared with the CME (figure kindly provided by B. Podlipnik).

the LASCO coronagraph on SOHO, is plotted in Fig. 3. The gas and magnetic field ejected during a CME require roughly a day to reach the Earth (if ejected in the right general direction). Once they do, they are a source of disturbances to the Earth's space environment (e.g. causing substorms in the magnetosphere) and cause magnificent auroral displays. They are also a nuisance and a danger that can damage sensitive technology (satellite safety, reliability of electronic communications, stability of the electric grid, etc.). They can even be a danger to human health (e.g. to astronauts or to crew and passengers of airplanes flying polar routes). Not all the material ejected during a CME manages to leave the Sun. Some of it may not escape the Sun's gravitational tug and spectacularly fall back down again, as illustrated in Fig. 4.

The above examples show some of the exciting phenomena occurring on the Sun. Nonetheless, although we have reached a level of detail and understanding that is vastly superior to what was possible just some years ago, thanks largely to the extraordinary instruments that have become available in the course of the last decade, the gaps in our knowledge are still considerable and will require further observations with instruments that go beyond the capabilities of the ones currently working. Such instruments will be provided by the reflight of the Sunrise balloon-borne observatory, the launch of the Solar Orbiter and the Solar C missions, as well as by the next generation of ground-based solar telescopes, in particular the European Solar Telescope (EST).

3. SOHO mission profile and outstanding results

SOHO has been the flagship solar and heliospheric mission for one and a half decades. The payload (for details, cf., Domingo et al. 1995) comprises both in-situ and remote sensing instrument suites. The latter consist of the EUV camera EIT (Delaboudinière et al. 1995), the white-light coronagraph LASCO (Brueckner et al. 1995), the vacuum-UV coronagraph spectrometer UVCS (Kohl et al. 1995), the high-resolution vacuum-UV slit spectrometers CDS (Harrison et al. 1995) and SUMER (Wilhelm et al. 1995), and the GOLF (Gabriel et al. 1995) and MDI (Scherrer et al. 1995) instruments for helioseismic measurements, with MDI also providing magnetograms. The particle instruments CELIAS (Hovestadt et al. 1995), COSTEP (Müller-Mellin et al. 1995), ERNE (Torsti et al. 1995), and the Lyman-α sky mapper SWAN (Bertaux et al. 1995) study the solar wind, while the Total Solar Irradiance (TSI) is monitored by VIRGO (Fröhlich et al. 1995).

Such a complete instrumentation suite has never been flown before. Until now, SOHO has delivered more than 4300 articles in refereed journals, making it second to none

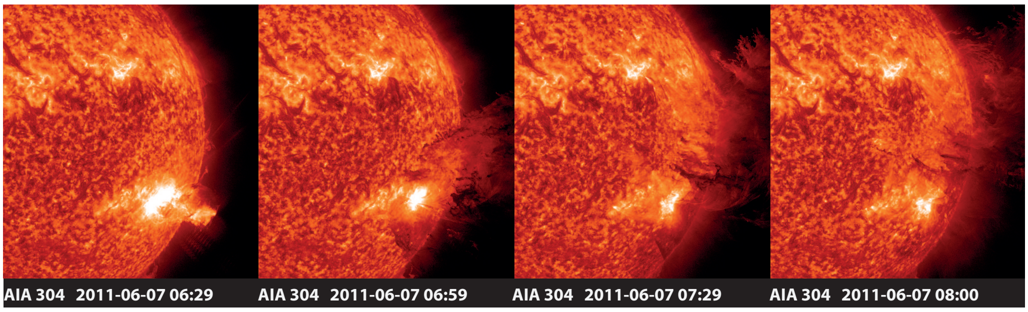

Fig. 4. A failed coronal mass ejection (CME) caught by the AIA imagers onboard the Solar Dynamics Observatory (SDO) in the He 304 Å channel (Pesnell et al. 2012). Figure kindly provided by B. Podlipnik.

in the ESA program (excepting the Hubble Space Telescope, a much larger mission). Representative for the many outstanding results achieved by SOHO a selection of three highlights is presented here.

3.1. The source of the fast solar wind

The correlation between the reduction of the soft-X-ray flux from disk center due to the transit of a coronal hole (a region of mostly open magnetic field where the corona is less dense and cooler) and the increase in the plasma bulk velocity was the first experimental evidence that the fast solar wind (i.e. wind with a large speed of 400 to 800 km s^{-1} at 1 AU) is coming from the open field regions of the Sun (Krieger et al. 1973). These results were confirmed and extended by the extremely successful Ulysses mission of ESA (1990 – 2009). Ulysses carried a payload of in-situ instruments over a solar polar orbit that allowed the first-ever survey of the Sun's environment in space from the equator to the poles, and over a wide range of solar activity conditions. A key result was the clear identification of the large coronal holes characterizing the poles of the Sun as the source region of the fast wind (e.g., Woch et al. 1997).

However, the details of where exactly in the coronal hole the wind emerges from and how it is accelerated remained unclear. One of the main science goals of SOHO was to identify the sites where the wind originates and to determine the nature of its acceleration.

Hassler et al. (1999) have used spectroscopic observations of SUMER to show that the sources of the fast solar wind are located along the boundaries of supergranular cells in coronal holes. This work has been expanded by Tu et al. (2005) into a 3D-configuration by employing magnetic field extrapolations. Previously it was believed that the fast solar wind originates in the layer where hydrogen becomes ionized, less than 2 Mm above the photosphere. These observations, however, establish that the bulk of the outflow has not yet occurred at a height of 5 Mm, but is present at 20 Mm. Tu et al. (2005) have proposed that the solar wind plasma is supplied by initially closed magnetic loops that are swept by convection to funnel regions where they undergo reconnection with existing open field lines, thereby releasing and accelerating previously confined plasma to form the solar wind. This result is obtained from a correlation of the Doppler-velocity and radiance maps of spectral lines emitted by various ions with the force-free magnetic field extrapolated from photospheric magnetograms to different altitudes. Specifically, they find that Ne^{+7} ions mostly radiate around 20 Mm, where they have outflow speeds of about 10 km s^{-1}, whereas C^{3+} ions with no average flow speed mainly radiate around 5 Mm. Based on these results, a model for understanding the solar wind origin is suggested as shown in Fig. 5.

At greater distances from the solar limb (from 0.5 up to about 4 solar radii above it), UVCS has allowed determining the main characteristics of the fast solar wind. As an exam-

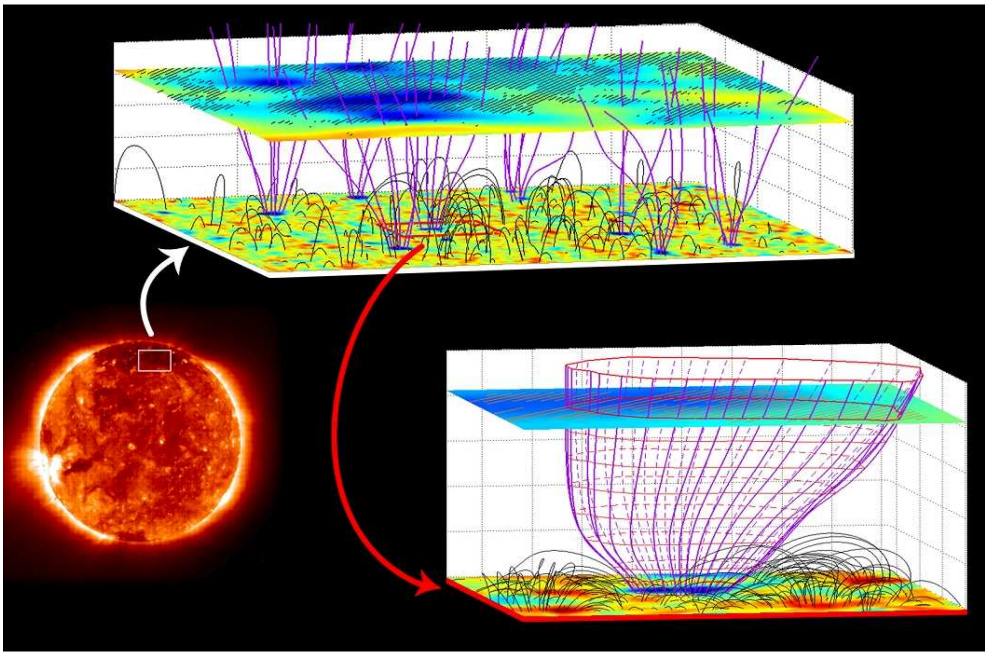

Fig. 5. Sketch of the magnetic and outflow geometries in a coronal hole region, where the fast solar wind originates. The polarities of the vertical component of the magnetic field at the solar surface are shown in blue and red. By extrapolation of these MDI measurements a 3D-configuration was calculated; open magnetic field lines are illustrated in magenta, closed ones are shown in grey, dark grey arches show closed ones. The elevated plane shows Ne^{7+} Doppler shift from SUMER (hatched regions have large outflows). At this height locations with high Doppler flow correlate with funnels of open field lines. (Courtesy: ESA/NASA. Figure was taken from a NASA press release).

ple, the outflow speed profile of O^{5+} and protons has been obtained (e.g., Cranmer et al. 1999) finding that the oxygen ions stream out faster than the protons. UVCS spectra have also revealed that spectra lines exceed the expectations from thermal broadening by a factor between about 3 in the case of the H I Lyman α line and 100 in the case of O VI lines indicating energy deposition in the region where the wind is being accelerated (see e.g., reviews of Antonucci et al. 2011; Kohl et al. 2006, and references therein). Note, however, that Raouafi & Solanki (2004) and Raouafi & Solanki (2006) found the excess broadening to be well reproduced by the outflow of the solar wind if one considers it to further distances where it has a strong line-of-sight component even above the limb. Hence, the evidence for extra energy deposition is not clear.

3.2. Four new comets every week

LASCO, SOHO's white light coronagraph was designed to observe the outer solar corona with its three units, C1. C2, and C3, each of which covers a different radial range, starting at 1.1 $R_\odot$ (C1) and ending at 32 $R_\odot$ (C3). Although LASCO was designed primarily to observe the solar corona, it turned out that the dark sky and the optical system with reduced straylight made it a perfect comet finder. During the first ten years of operation, 1000 new comets were discovered with LASCO data. Most of the discoveries were completed by students, hobby astronomers or other comet hunters using data from the publicly accessible SOHO archive. The increasing size of this community is one of the reasons, why it took only five years to double this number. In December 2011, SOHO discovered its 2000th comet. Drawing on this world-wide community, SOHO has become the greatest comet finder of all times. Approximately 85% of the comets discovered with LASCO are thought to come from a single group known as the Kreutz family, believed to be the remnants of a single large comet that broke up several hundred years ago (Sekanina 2002). The Kreutz family comets are "sungrazers" – bodies whose orbits approach so near the Sun that most are vaporized within hours of discovery – but many of the other LASCO comets like 96P/Machholz shown in Fig. 6 swing around the sun and return periodically.

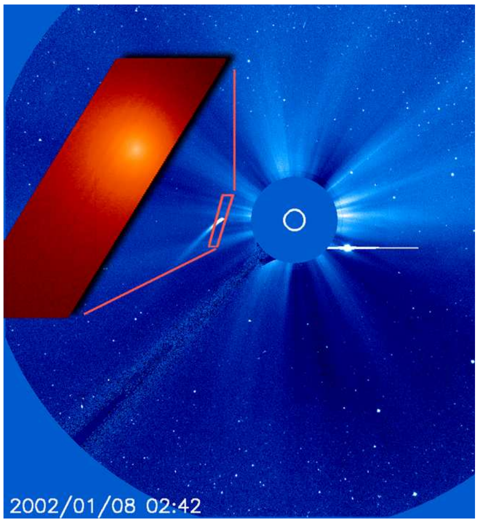

Fig. 6. Composite of a LASCO C3 image and an UVCS insert showing comet Machholz after an orbit of 63 months again approaching the Sun at a distance of 22 million kilometer in January 2002. Venus is also in the field of view (saturating the detector). In the far ultraviolet light of Lyman-α (121.6 nm) only the bright coma of the comet is seen (Bemporad et al. 2005). These observations allow an estimate of the density of the impinging solar wind to be given at the position of the comet. (Courtesy: ESA/NASA. The figure was taken from a NASA press release).

3.3. The total solar irradiance

The total solar irradiance, which was known as the solar constant before it became clear it is variable, is of prime interest for studies of the Sun's influence on the Earth's climate. The 17 year long TSI record from the VIRGO radiometers, and insights about the dose of radiation received by the detectors – the main cause of instrument degradation for any TSI monitor – allowed the PI team to develop a model (Fröhlich 2006) for the degradation of the VIRGO as well as of the ACRIM-I and NIMBUS-7 instruments. With this model it is now possible to correct the results of these radiometers accordingly, and hence construct a composite TSI record over the last 26 years shown in Fig. 7. Other composites of TSI have also been produced, e.g., by Dewitte et al. (2004), but this one shows a long-term trend that agrees best with the most advanced models (Wenzler et al. 2009; Ball et al. 2012). From this composite record, it now appears that (i) there is a long-term, secular trend, with the just ended minimum lying lower than earlier ones (Fröhlich 2009), and (ii) the average amplitudes of the three cycles are within 10% and slightly decreasing from 0.93 to 0.82 Wm^{-2}, although each maximum looks quite different. Although this record is in itself too short to deduce clear effects of the Sun on climate, it does play a very important role in calibrating models of solar irradiance. The most advanced such models assume that the solar irradiance is changed on time scales of days to millennia by magnetic fields at the solar surface (Krivova et al. 2003; Domingo et al. 2009). The success of such models can be judged from Fig. 7, where, in addition, to the measured TSI also the results of modelling by Ball et al. (2012) are plotted. From such work we can conclude that over 90% of the TSI variations are due to the evolution of the magnetic field at the so-

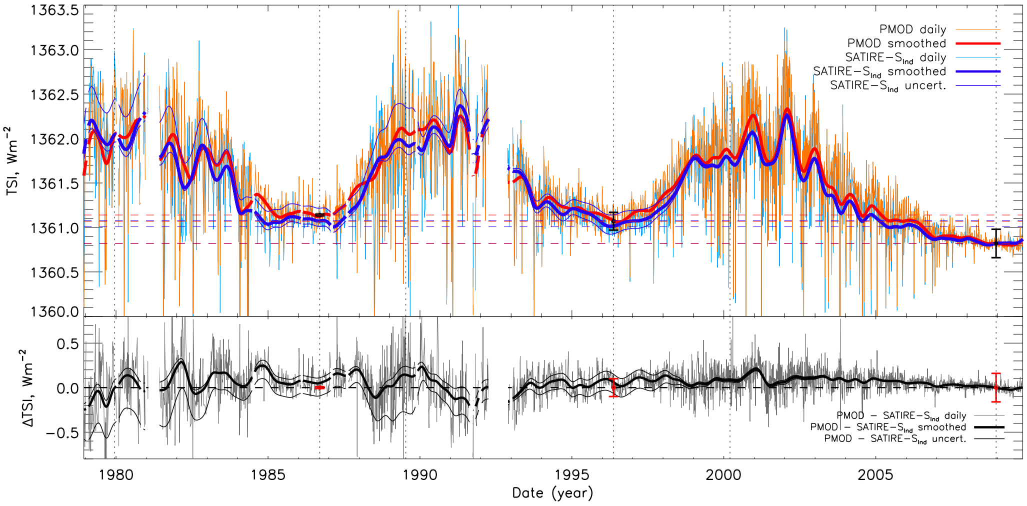

Fig. 7. The composite total solar irradiance (TSI) since 1978, i.e. over three solar cycles, combining data from multiple spacecraft instruments, put together by Fröhlich (2006) is plotted in the upper panel (light red line: daily data, thick red line: smoothed data). TSI reconstructed by the SATIRE model is overplotted (light blue line: daily values, thick blue line: smoothed values). The lower panel shows the difference between the TSI from PMOD and SATIRE (daily: grey lines; smoothed: black lines). From Ball et al. (2012).

lar surface. Such models can, after their validation by the measured TSI composites, be used to reconstruct irradiance further back in time, e.g. to the year 1610 using the sunspot numbers record as a proxy of freshly emerged magnetic fields and computing the evolution of the magnetic field at the solar surface starting from there. If we compare the resulting total solar irradiance since roughly 1850 years with the global climate record available since then, it becomes clear that although solar irradiance variations may have contributed to climate changes up to around 1970, they display a totally different trend than the climate since roughly 1970, so that they can hardly have contributed to the significant warming of the Earth since then.

3.4. Outlook

Since the launch of NASAs Solar Dynamics Observatory (SDO), the role of SOHO has changed towards being a supporting, but still essential component of the armada of heliophysical observatories, namely SDO, and both STEREO spacecraft. In particular, SOHO's LASCO coronagraph has become a critical element of the International Living With a Star (ILWS) program providing the third eye for the STEREO view. In addition, SOHO will continue to provide important measurements of total solar irradiance, low-frequency global solar oscillations, energetic particles and solar wind plasma parameters. The scientific harvest from the SOHO mission is not over yet. Plans for a mission extension beyond 2014 are being discussed. Thanks to its still unique instruments, SOHO has the potential of providing a lot more exciting science also in the future.

4. Follow-on missions in operation

4.1. STEREO, Hinode, Proba 2 and others

SOHO has been an incredible success, measured both in terms of the huge number of publications based on SOHO data and the revolution it has created in our picture of the Sun. This success and the revitalized interest in the Sun has spawned many new solar missions world-wide. These include the NASA missions TRACE (Handy et al. 1999), RHESSI (Lin et al. 2002), STEREO, with a strong European contribution (Kaiser et al. 2008), SDO (Pesnell et al. 2012), the japanese-led Hinode mission (also with a considerable European contribution) and the purely European Proba 2 (Berghmans et al. 2006) as well as the European-led Sunrise, a stratospheric balloon-borne obsevatory (Solanki et al. 2010; Barthol et al. 2011). Below we discuss those of these missions that have a significant European contribution.

4.1.1. Hinode

Hinode is a mission to study the Sun at high resolution over a broad range of wavelengths (Kosugi et al. 2007). It has 3 main telescopes, with the SOT (Solar Optical Telescope) being by far the largest with a primary mirror having a diameter of 50 cm (Tsuneta et al. 2008). This telescope, which is fully integrated with the spacecraft structure, feeds 3 post-focus instruments, the broad-band filter imager (BFI), the narrow-band filter imager (NFI) and the spectropolarimeter (SP). The other two telescopes are the Extreme-ultraviolet Imaging Spectrometer (EIS) (Culhane et al. 2007) and the X-Ray Telescope (XRT) (Golub et al. 2007). One of the big discoveries by Hinode was the detection of magnetic field all over the quiet Sun (in particular in the so-called internetwork, i.e. the region lying between the network of strong magnetic fields that covers the Sun), which has become a hot topic (Lites et al. 2008; Orozco Suárez et al. 2007) and has had considerable resonance in modelling (Steiner et al. 2008; Schüssler & Vögler 2008; Danilovic et al. 2010b).

A remarkable success has been the understanding that the emergence of magnetic flux is often a very complex process. It could be shown that this complexity occurs because the underlying emerging monolithic magnetic flux tube is shredded into many smaller flux bundles by the convection (Cheung et al. 2008). Hence, flux emerges not as a single Ω-loop, but rather as many small such loops that merge with each other after some time to partly re-form the larger underlying flux tube (whose cross-section may appear as a sunspot at the solar surface). Another remarkable discovery has been the large number of X-ray jets observed particularly in the polar coronal holes (Cirtain et al. 2007). A success has been the reproduction of the properties (such as velocities and time-scales) of X-ray jets by 3-D models of emerging magnetic flux in the presence of pre-existing field by Moreno-Insertis et al. (2008), which extends earlier work by Yokoyama & Shibata (1995).

The X-ray telescope also provided the first evidence of continuous plasma outflows from the edges of active regions (Sakao et al. 2007). The EIS spectrometer confirmed these apparent motions to be persistent high speed outflows (see Fig. 8) from large, relatively faint, areas at the periphery of many active regions (e.g., Harra et al. 2008; Doschek et al. 2008). These outflows are characterized by bulk shifts in the line profile of up to 50 $\mathrm{km\,s^{-1}}$ and enhancements in the blue wing of up to 200 $\mathrm{km\,s^{-1}}$ (e.g., Bryans et al. 2010). These outflows are of interest because they may lie on open field lines and, thus, could indicate one of the still mostly mysterious source regions of the slow (300 to 400 $\mathrm{km\,s^{-1}}$) solar wind. For example, using magnetic field extrapolations Schrijver & De Rosa (2003), showed that active region fields are often connected to the heliosphere and suggested that up to 50% of the heliospheric field may originate in and around solar active regions. The connection to the slow wind is also supported by the finding that the chemical composition of the outflowing plasma is compatible with that of the slow wind (Brooks & Warren 2011).

Hinode has greatly profited from a relatively large telemetry. This is particularly important for solar missions, where the very high photon flux from the Sun, permits following the solar dynamics at the required high spatial resolution. This translates into a high information rate that the Sun provides in comparison with most other astronomical objects. The significant contribution of European ground stations has been very important at ensuring an adequate telemetry rate to Hinode, particularly after the loss of the on-board X-band transmitter.

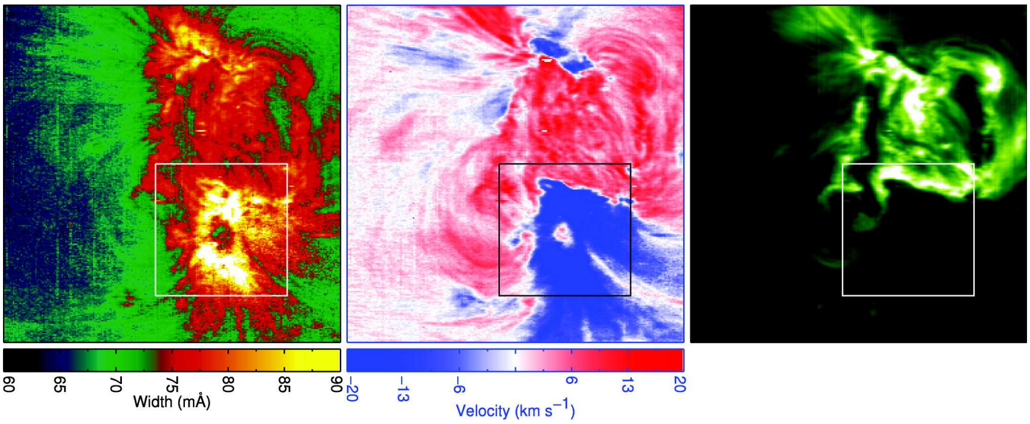

Fig. 8. EIS measurements of the Doppler width (*left*), shift (*center*), and intensity of the Fe xii 19.5 nm line from single-Gaussian fitting. The figure shows the substantial outflow emerging from a large, dark, area at the periphery of the active region. Part of Figure 4 of Doschek et al. (2008). Reproduced by permission of the AAS.

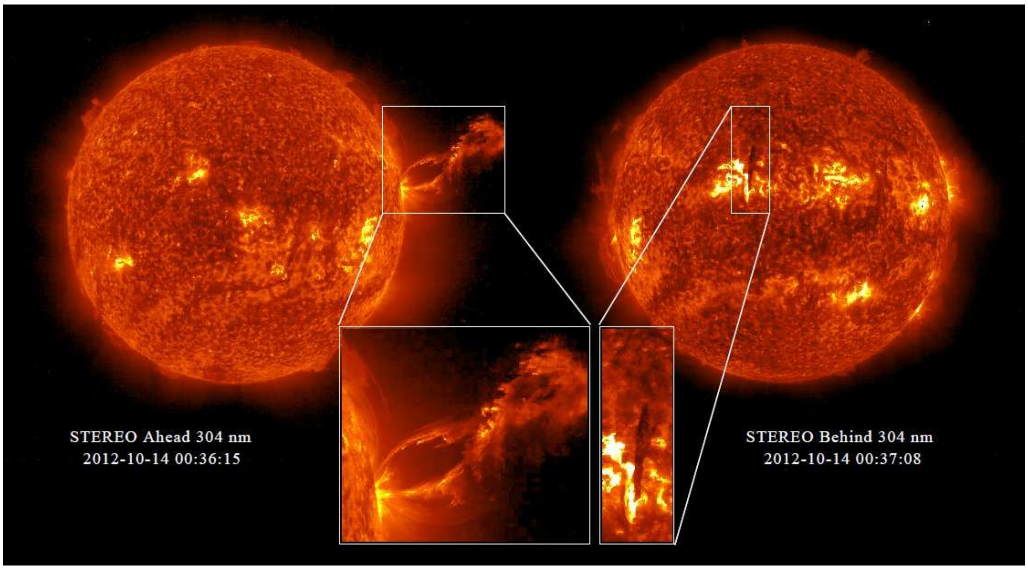

Fig. 9. Gigantic twisted prominence rising fom the solar surface on 14 Oct 2012. The extent of the prominence system is well visible fom the viewpoint of STEREO-A, while it is seen almost head on and hardly visible from STEREO-B (see insert). At the time of these observations, the two STEREO spacecraft were 114 degree apart in heliographic longitude.

4.1.2. STEREO

With the launch of the two STEREO spacecraft on 27 October 2006, solar physics entered a new area. Since then, two equally constructed space probes orbit the Sun on independent, slightly elliptic orbits near ∼1 AU. One spacecraft is ahead of Earth's heliographic longitude, the other lags behind. The longitudinal distance of each spacecraft to Earth increases on average by 22 degrees/year and has now (end of September 2012) reached about

120 degrees, so that together with a spacecraft in the direction of the Earth (SOHO or SDO), STEREO can image all solar longitudes. Details of the remote-sensing instrumentation SECCHI of the STEREO mission can be found in Howard et al. (2008).

For the first time, the Sun could be observed from viewpoints in space markedly different from the Earth's position. How remarkably different a solar structure can appear from the different viewpoints of the two STEREO spacecraft is illustrated in Fig. 9. The two images were taken at the same time, during the eruption of a large filament/prominence (filaments and prominences describe the same phenomenon, once seen as a dark band on the solar disk (as in the image on the left), once as a bright structure off the solar limb (image on the right). From the image on the left alone, it would never have been possible to determine the complex structure of the erupting feature.

Even though the mission was primarily devoted to the investigation of solar eruptions and the propagation of mass ejecta in the near-Sun heliosphere, right from the beginning of the mission its high-resolution EUV imagers revealed a new wealth of rapid and small-scale EUV fluctuations along loops in the transitions region and low corona in regions which were hitherto considered to be quiescent. The reconstruction of the 3D geometry of bright EUV loops from the STEREO data served two purposes. Firstly, the knowledge of the true geometrical shape of bright magnetic flux tubes helped to derive more reliable emissivities, disentangled from the line-of-sight integrated weighting of the observed EUV intensities along the loops. These emissivities constrain the models which simulate plasma transport, radiation and heating processes on magnetic loops. The other benefit from the knowledge of the geometrical shape of individual loops is that they trace out the magnetic field and hence give, in addition to field extrapolation calculations, an idea of the topology of the coronal magnetic field.

Time series of the loop reconstructions revealed at times systematic oscillations of loops. Frequency, polarization and damping rate allow the properties of the coronal plasma and magnetic field to be constrained even in a wider environment around the oscillating loop. A comprehensive review of loop reconstructions is given by Aschwanden (2011) Other objects whose 3D structure can be reconstructed are so-called plumes which originally were considered to be field-aligned striations of dense plasma emanating from coronal holes. The attempt to reconstruct their surface distribution from STEREO observations showed that they rather consist of a superposition of localised striations and a curtain-like network of dense plasma (Wilhelm et al. 2011; de Patoul et al. 2011).

The stereoscopic reconstruction of mass ejecta turned out to be more difficult than anticipated. The first studies concentrated on the determination of the barycentre propagation direction. These parameters can now be deduced reliably from the STEREO coronagraph observations and are essential for the prediction of the geo-effectiveness of a mass ejection, i.e., its probability to impact the Earth's magnetosphere (Mierla et al. 2010). It turned out that the two views provided by the STEREO probes are in most cases not sufficient to obtain a decent estimate of the size and shape of the mass ejection. Additional observations from the SOHO/LASCO coronagraphs add a third, independent view direction and improved the mass ejection models substantially (Feng et al. 2012). The STEREO remote sensing instrumentation is essentially a heritage of the SOHO mission and includes Sun-centred coronagraphs and an EUV imager with, however, better resolution than the SOHO/EIT instrument. The exceptions onboard STEREO are the heliospheric imagers. These are a new type of off-axis coronagraphs covering the entire space between Sun and Earth. With both these objects sufficiently occulted, the instrument sensitivity could be driven to the detection level of stars of magnitude 19. The enhanced plasma densities of mass ejecta from the Sun Thomson-scatter the sunlight even at distances of almost 1 AU so that the ejecta become visible in (well preprocessed) images from the Heliospheric imagers. Determinations of the mass ejectum propagation direction and travel time estimates to 1 AU were successfully performed from these observations (Lugaz et al. 2012). Moreover, the evolution of the plasma cloud of several mass ejecta could be tracked out to almost 1 AU. These observations revealed the gradual transition of the plasma cavity typically seen in mass ejecta close to the Sun to the magnetic cloud observed in-situ in particle data onboard space craft at 1 AU (Howard & DeForest 2012; Webb & Howard 2012). Fast mass ejecta (faster than the local fast magnetosonic speed) develop a shock ahead of their magnetic cloud which could also be observed by the heliospheric imagers out to about 0.5 AU (Maloney & Gallagher 2011).

4.1.3. Proba 2

After the successful Earth-observing Proba 1 satellite, ESA's Project for On-Board Autonomy (PROBA) continued with the launch on November 2009 of a further Earth-orbiting micro-satellite. As part of ESA's in-orbit Technology Demonstration programme, Proba 2 carries many technology demonstrators but also four scientific experiments, two of which (LYRA and SWAP) are dedicated to solar studies. The Large-Yield Radiometer (LYRA, Hochedez et al. 2006; Benmoussa et al. 2009) is equipped with innovative diamond detectors that are insensitive to visible light. It measures the solar irradiance with high temporal resolution (about 20 Hz) in four spectral bands respectively at Soft-X, EUV (corona), FUV (hydrogen Lyman α: chromosphere) and UV (upper photosphere) wavelengths. As an example, the temporally resolved irradiance can provide information on flaring structures via coronal seismology (see, e.g. , Van Doorsselaere et al. 2011). The Sun Watcher Using APS Detectors and Image Processing (SWAP) provides images of the solar corona in a ≈ 15 Å wide EUV bandpass centered at 17.4 nm (Seaton et al. 2012; Berghmans et al. 2006). With a field-of-view of about $54' \times 54'$ (about 3.4×3.4 solar radii), a pixel size of $3.2''$ and a nominal cadence of less than 2 min, SWAP is particularly suited at studying intermediate (from few Mm) to large-scale (up to about one solar radius) coronal structures (see e.g., Habbal et al. 2011; Pasachoff et al. 2011), and their dynamical evolution (eruptive prominences: Mierla et al. 2012, eruption-triggered coronal waves: Kienreich et al. 2012, and coronal mass ejections: Temmer et al. 2011).

4.2. Sunrise

SUNRISE is a balloon-borne solar observatory dedicated to the investigation of the key processes governing the physics of the magnetic field and the convective plasma flows in the lower solar atmosphere (Solanki et al. 2010). These processes are crucial for our understanding of the magnetic activity of the Sun and of the outward transport of energy to heat its outer atmosphere and to fuel the eruptions and coronal mass ejections, i.e. phenomena that also affect the Earth system. SUNRISE is designed for operation in the stratosphere (at heights around 36 km) in order to avoid the image degradation due to turbulence in the lower terrestrial atmosphere and to gain access to the UV range down to 200 nm wavelength. Launched from above the polar circle at solstice conditions, SUNRISE enables an uninterrupted view at the Sun for extended periods of several days. This mission concept combines the advantages of space-borne telescopes – undisturbed observations from above the atmosphere – with the advantages of ground based instrumentation. The downside is that a balloon flight lasts only a fraction of the time that a spacecraft is in orbit. However, the instrument can be recovered, refurbished or improved and reflown at a fraction of the cost of a space mission. SUNRISE features the largest solar telescope ever to leave the ground. Equipped with an extremely light-weighted primary mirror of 1 m diameter, the Gregory-type telescope feeds a high-resolution UV imager and a very sensitive imaging spectropolarimeter, providing maps of the solar surface magnetic field and line-of-sight velocity of the plasma flows (Barthol et al. 2011). At float, hanging about 100 meter below a 1 million cubic meter helium balloon, the telescope is actively pointed towards the Sun by a gondola structure, which provides a pointing accuracy of fractions of an arcminute for ex-

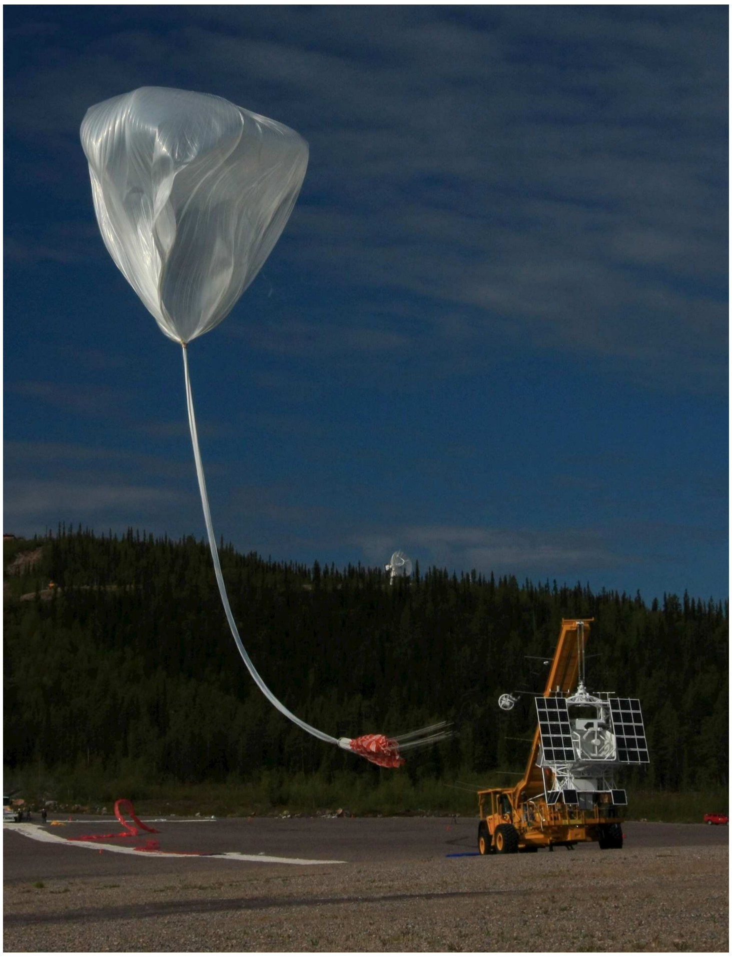

Fig. 10. The SUNRISE payload (in the foreground) just prior to launch on 8th June 2009, at ESRANGE, near Kiruna in northern Sweden. In the background, the stratospheric balloon has just been released and is slowly rising. The total weight (including the balloon and helium) is roughly 6 tons, with a payload mass of 2 tons.

tended periods. Residual image motion is effectively suppressed by a piezo-driven tip-tilt mirror inside the instrument package, aiming at an image stabilization of < 0.1 arcsec. A wavefront sensor located in the instrument package constantly monitors and controls the alignment status of the optics (Berkefeld et al. 2011).

The SUNRISE filtergraph provides high-resolution, high-cadence imaging of photospheric and chromospheric features at 5 wavelength bands of interest in the near ultraviolet (Gandorfer et al. 2011a). The second science instrument onboard SUNRISE is an imaging vector magnetograph, developed for observations of Doppler shifts and polarization in the highly Zeeman-sensitive photospheric spectral line of Fe I at 525.02 nm (Martínez Pillet et al. 2011). The instrument provides fast-cadence two-dimensional maps of the complete magnetic vector, the line-of-sight velocity, and continuum frames with high spatial resolution.

SUNRISE had a successful first science flight in June 2009 (Fig. 10), starting from Kiruna, Sweden (68° latitude), and landing on Somerset Island, Canada at a latitude of 74°. This flight provided data with unprecedented spatial resolution and the highest contrasts ever measured at the Sunrise wavelengths, data that have changed our view of the quiet Sun, showing that even the seemingly least active parts of the solar atmosphere are pervaded by large amounts of magnetic flux in constant dynamical interaction with the convective motions. The main results derived from Sunrise can be summarized as follows:

- A breakthrough achieved by Sunrise was that small-scale intense magnetic flux concentrations, the so-called magnetic elements, were resolved for the first time (Lagg et al. 2010). Their existence was indirectly deduced already 40 years ago (Stenflo 1973), but only the high spatial resolution of Sunrise allowed them to be finally resolved, first steps to determine their internal magnetic structure have also been undertaken by Martínez González et al. (2012). They have been found to be unexpectedly bright in UV wavelengths as well, displaying intensities up to a factor 5 above the mean brightness at 214 nm (Riethmüller et al. 2010).
- Measurements of the RMS intensity contrast of granulation in the UV show high values of up to 30 %, consistent with numerical simulations. These values provide a direct measure of the efficiency of convective energy transport by granulation (Hirzberger et al. 2010).
- The magnetograph provided most sensitive high-resolution time sequences of maps of the vector magnetic field ever obtained. They reveal abundant small-scale fields, which are very dynamic and show high rates of flux emergence and cancellation (Danilovic et al. 2010a).
- Ubiquitous small-scale whirl flows are found (Steiner et al. 2010), some of which drag small-scale magnetic field structures into their centres (Bonet et al. 2010).
- The measurements show localized supersonic vertical flows. Their connection with strong heating and association with nearby opposite-polarity magnetic fields indicate the occurrence of current sheets and field line reconnection processes in the middle photosphere (Borrero et al. 2010).
- Magnetic field extrapolations indicate that most magnetic loops in the quiet Sun remain within the photosphere. Only a small fraction reaches the chromosphere. Most of these higher-lying loops are anchored (at least in one foot point) in the strong-field elements of the network (Wiegelmann et al. 2010).
- Large amplitude propagating acoustic / magneto-acoustic waves in the quiet solar chromosphere were discovered (Bello González et al. 2010; Martínez González et al. 2011). Such waves were missed in the past, since they are strongly localized and their photospheric sources move significantly in the course of a few wave periods.

The first SUNRISE flight took place during a time of very low solar activity. The success of the first flight and the recovery of the largely intact instrumentation have shown the huge potential of the SUNRISE approach.

A reflight is planned in 2013, at a time when the present activity cycle should reach its maximum. This would allow studying the active Sun, in particular the magnetically active regions including sunspots, plage, flares etc. with highest spatial resolution.

5. Forthcoming and Future missions

5.1. Solar Orbiter

As described in the previous sections, the various past and present European and international space (and stratospheric) missions dedicated to the study of the solar atmosphere have

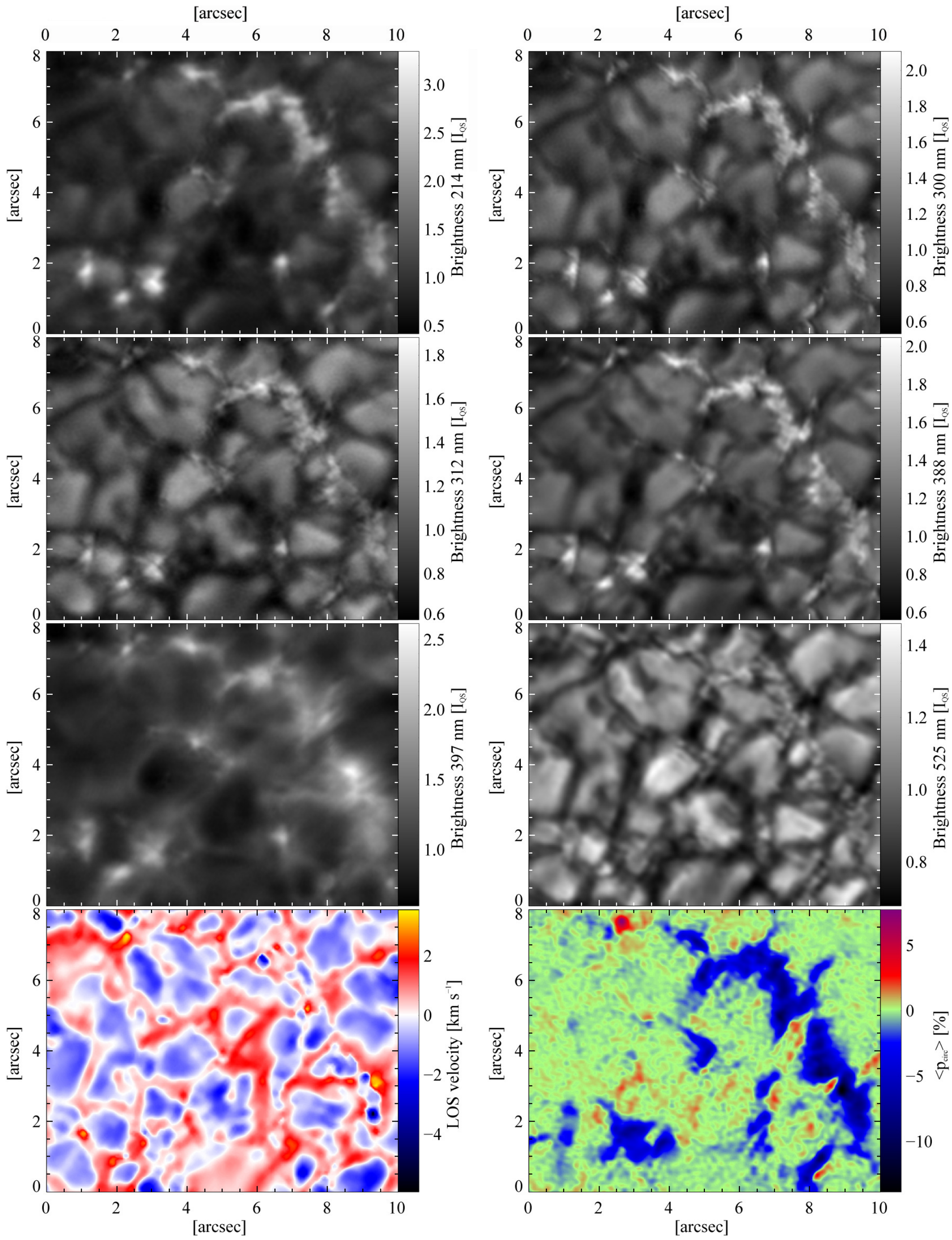

Fig. 11. Intensity maps of the five wavelengths observed by SuFI (two first rows and the left panel of the third one) and of the continuum sample by IMaX (the right panel of the third row), all normalized to the corresponding mean intensity level of the quiet Sun, IQS. The LOS velocity obtained from a Gaussian fit (positive velocities correspond to downflows) and the mean circular polarization degree are shown in the bottom panels. Figure kindly provided by T. Riethmüller (adapted from Riethmüller et al. 2010).

shown an ever-changing dynamic atmosphere shaped by the magnetic field that emerges from the solar surface and drives, in ways not yet fully understood, the mass and energy flow from the stellar interior into the solar corona. The flux of mass and energy not only creates and sustains the corona but also expands into interplanetary space both continuously (as the solar wind) and abruptly (e.g., coronal mass ejections occurring as consequence of flares and/or prominence eruptions) forming the solar heliosphere. So far, solar observations have always been performed from the ecliptic plane, leaving the polar regions of the Sun far less well explored. In parallel to the remote sensing studies, many instruments and mission have been dedicated to the in-situ measurement of the physical conditions (e.g., chemical composition, ion fractionation, velocity distributions) of the heliospheric plasma at various distances from the Sun. The rising awareness of the need of studying the Sun and its heliosphere as a coupled system (all processes studied in the Heliosphere finally have their origin in the solar atmosphere) has led the European solar community to propose a mission orbiting the Sun as close as 0.28 AU and able to leave the ecliptic plane with a payload of remote sensing and in-situ instruments. The mission, named "Solar Orbiter", is now approved and is scheduled for launch in 2017 within the Cosmic Vision programme of ESA and in collaboration with NASA. In fact, understanding how the Sun and its magnetic structures are connected with and affect the heliosphere is of fundamental importance to address one of the major scientific questions of ESAs Cosmic Vision programme: "How does the Solar System work?"

5.1.1. Mission science goals

To fulfill the mission primary science goal of understanding "*How does the Sun create and control the heliosphere?*", Solar Orbiter needs to answer the following main science questions (taken from ESA's Solar Orbiter Definition Study Report):

- *How and where do the solar wind plasma and magnetic field originate in the corona?*
- *How do solar transients drive heliospheric variability?*
- *How do solar eruptions produce energetic particle radiation that fills the heliosphere?*
- *How does the solar dynamo work and drive connections between the Sun and the heliosphere?*

Answering the above questions, requires in-situ measurements of the solar wind plasma, magnetic fields, waves, and energetic particles close to the Sun, before they had their properties modified by transport and propagation processes. Identifying the regions and structures on the Sun from where the measured plasma is coming from requires simultaneous, high-resolution imaging and spectroscopic observations of the solar surface and inner corona in and out of the ecliptic plane. The capability of performing combined in-situ and remote-sensing observations from the same spacecraft at close distances and from different viewpoints, makes Solar Orbiter a truly unique mission. To achieve its ambitious science goals, Solar Orbiter will be inserted into an elliptical orbit that will periodically take it to distances down to 0.28 UA and into phases of quasi co-rotation with our star. Moreover, thanks to gravity assisted maneuvers, the orbit will be progressively inclined with respect to the ecliptic plane, gaining an unprecedented view of the polar regions of the Sun.

5.1.2. Payload

Solar Orbiter will carry a payload (see Fig. 12), provided by ESA member states and NASA, of in-situ (Table 1) and remote sensing (Table 2) instruments that will allow a systematic study of the heliosphere and its sources on the solar surface.

Solar Orbiter carries a full complement of remote sensing instruments, including a helioseismology and magnetic field instrument, an imager and a spectrometer operating in the far to extreme ultraviolet, a coronagraph capable of spectroscopic measurements and an X-ray telescope. An overview of the remote-sensing instruments is given in Table 2. The closeness to the Sun reached at perihelion poses a great

Table 1. In situ instruments of the Solar Orbiter payload (extracted from the Solar Orbiter definition study report).

Instrument	Measurement	Technique
Solar Wind Analyzer (SWA)	Solar wind ion and electron bulk properties, ion composition (1 eV - 5 keV electrons; 0.2 - 100 keV/q ions)	Multiple sensors (electrons, proton/alpha, heavy ions); electrostatic deflection, time-of-flight measurement, solid state detectors
Energetic Particle Detector (EPD)	Composition, timing, and distribution functions of suprathermal and energetic particles (8 keV/n 200 MeV/n ions; 20-700 keV electrons)	Multiple solid-state dE/dx vs E detector telescopes, time-of-flight measurement
Magnetometer (MAG)	DC vector magnetic fields (0 64 Hz)	Dual fluxgate sensors
Radio and Plasma Waves (RPW)	AC electric and magnetic fields (~DC 20 MHz)	Electric antennas, Search Coil Magnetometer; Low-frequency and Thermal Noise/High-frequency receivers, Time-domain sampling

technical challenge to the spacecraft manufacturing and, particularly, to the remote sensing instrumentation. In fact, the large heat flux impinging on the thermal shield imposes modest apertures to these instruments. On the other hand, the close distance translates a moderate angular resolution of 0.5″ to 2″ into a very high spatial resolution of 100 to 400 km at perihelion, consequently requiring short exposures to avoid dynamical blurring (gas flows of several tens of km s^{-1} are commonly observed in the corona even under quiet conditions). Finally, the flux at a given angular resolution in spatially resolved observations, is independent of the distance from the Sun. This combination of constraints and requirements calls for an extreme optimization of the instrument throughput by maximizing surface reflectivity and detector sensitivity while minimizing the number of optical surfaces. Finally, the high levels of radiation and particles (e.g., protons) expected at the closest distance impose particular care in the use of radiation hard components and the protection of the optical coatings. Active pixel sensors (APS) are the baseline for all the remote sensing instruments (apart from the X-ray imager that uses Cadmium-Zinc-Telluride (CZT) planar detectors). Here we give a brief description of the four larger remote sensing instruments aboard Solar Orviter.

Extreme Ultraviolet Imager (EUI): EUI (Halain et al. 2012) consists of two high resolution imagers (HRIs) taking images over narrow band-passes respectively centered on the hydrogen Lyman α line ($HRI_{Ly\alpha}$) at 121.6 nm (formed in the solar chromosphere around 20000 K) and around 17.4 nm (HRI_{174}, dominated by lines from Fe IX to XI formed at temperatures around 1 MK). These are two-mirror telescopes having an image scale of 0.5″/pixel over 2048×2048 detectors. $HRI_{Ly\alpha}$ (Schühle et al. 2011) uses two interference filters, one at the entrance aperture (also preventing most of the heat from entering the instrument) and one at the focal plane, to isolate the line of interest and an intensified detector (that is blind to visible light) to suppress the visible and infrared emission from the solar disk. HRI_{174} uses a combination of multilayer coatings on the mirror surfaces and thin aluminium filters to isolate the required band-pass. The other component of EUI is a single mirror full-Sun imager (FSI) able to select two different band-passes by using a filter wheel mounted at the focal plane. The telescope operates at 17.1 nm (Fe IX -X) or at 30.4 nm (dominated by the Lyman

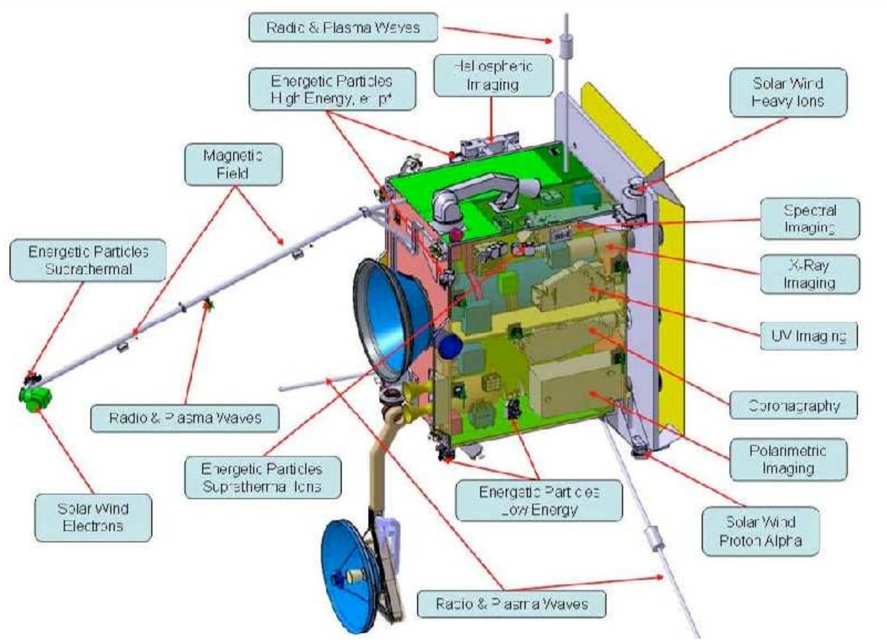

Fig. 12. Payload accomodation onboard Solar Orbiter (from the Solar Orbiter definition study report).

α line of singly ionized helium). The images have a scale of 4.45″/pixel over a 3072×3072 sensor.

Spectral Imaging of the Coronal Environment (SPICE): SPICE is a two element open (no entrance filters) instrument consisting of a single parabolic mirror creating an image of the Sun on the slit plane. The slit is then imaged and dispersed by a Toroidal Variable Line Space (TVLS) grating onto two detectors (70.4 nm – 79 nm, and 97.2 nm – 104.9 nm). The telescope mirror is a square parabola section made of fused silica coated with a 10 nm thick single-layer of B4C. The coating thickness is optimized to maximize reflectivity in the EUV while being mostly transparent to visible and near-IR light that can, thus, be redirected into a heat dump. A TVLS grating coated with a thick layer of B4C disperses the slit image onto two intensified cameras consisting of 1024×1024 APS sensors (1″ pixel) mated to MCP intensifiers coated with KBr to increase sensitivity in the EUV. Those detectors are insensitive to radiation above 200 nm. SPICE has a spatial resolution of about 4″ and a spectral resolution and signal-to-noise high enough to measure flows down to about 5 km s^{-1}.

Multi Element Telescope for Imaging and Spectroscopy (METIS): METIS is an inverted-occultation coronagraph capable of performing broadband imaging and polarization (to observe the linearly polarized component of the K corona) in the visible range (between 590 and 650 nm), and narrow band imaging in FUV (H I Lyman α). In addition, it will acquire spec-

Table 2. Remote sensing instruments of the Solar Orbiter payload (extracted from the Solar Orbiter definition study report).

Instrument	Measurement	Technique
Polarimetric and Helioseismic Imager (PHI)	Vector magnetic field and line-of-sight velocity in the photosphere	High-resolution telescope: off-axis Ritchey-Chrtien; Full-disk telescope: refractor; Fabry-Prot filtergraph.
EUV Imager (EUI)	Full-disk EUV and high-resolution EUV and H I Lyman α imaging of the solar atmosphere	Full-Sun imager: dual-band EUV off-axis Herschelian; High-res. imagers (2): EUV (Cassegrein) and H I Lyman α (Gregory) off-axis telescopes.
X-ray Spectrometer Telescope (STIX)	Solar thermal and non-thermal X-ray emission (4 150 keV)	Fourier transform imaging, CZT detectors
Multi Element Telescope for Imaging and Spectroscopy (METIS)	Visible, UV and EUV imaging and EUV (He II 30.4 nm) spectroscopy of the solar corona	Externally-occulted coronagraph with spectroscopic capabilities.
Heliospheric Imager (SoloHI)	White-light imaging of the extended corona	Wide-angle lens with aperture stop
Spectral Imaging of the Coronal Environment (SPICE)	EUV spectroscopy of the solar disk and low corona	Off-axis paraboloid telescope, TVLS grating spectrograph

tra of the solar corona in the He II 30.4 nm line simultaneously to FUV imaging. It will be equipped with two detectors: a hybrid APS dedicated to the visible channel and an intensified APS for the FUV/EUV channel. The EUV spectroscopic channel shares the same detector as the FUV corona imaging, with the spectrum imaged on a portion of the detector not used by the corona image.

Polarimetric and Helioseismic Imager (PHI): PHI (Gandorfer et al. 2011b) is a diffraction limited, wavelength tunable, quasi-monochromatic, polarisation sensitive (at a signal to noise level of 10^3 or better) imager. It is composed of two telescopes. The off-axis Ritchey-Chrétien High Resolution Telescope (HRT) will image a fraction of the solar disk at a resolution reaching about 200 km at perihelion. The Full Disk Telescope (FDT), a refractor, is capable of imaging the full solar disk at all phases of the orbit. Each telescope has its own Polarization Modulation Package (PMP) located early in the optical path in order to minimize polarisation cross-talk effects. The HRT and the FDT will sequentially send light to a Fabry-Perot filtergraph system ($\approx$ 100 mÅ spectral resolution) and on to two 2048×2048 pixel CMOS sensors for dual beam polarimetry. PHI will have its own Image Stabilization System (ISS) that will compensate spacecraft jitter or other disturbances. This system will be composed of a correlation tracker camera and a rapid tip-tilt mirror in the high resolution channel.

5.2. Solar C

The solar space missions of the last two decades have greatly increased our knowledge of the Sun's magnetized atmosphere, providing detailed observations of the morphology, structure and evolution of various structures such as coronal loops, prominences and sunspots and of eruptive phenomena such as flares and coronal mass ejections. Still, fundamental questions remain to be answered. What role does magnetic reconnection play in producing solar flares and coronal mass ejections? How are particles accelerated in the solar atmosphere? How is the solar wind energized and accelerated? How do small-scale sites of energy release determine the large-scale structures of solar activity? To answer these questions solar physicists in Japan, the United States, and Europe have been studying the possibility of a follow-on mission to the highly successful Solar-A (Yohkoh) and Solar-B (Hinode) programs that would make major steps forward in improving our understanding of the solar atmosphere.

Solar-C will study the dynamical coupling between the various components of the solar inner atmosphere (the first half solar radius above the surface), considered as an "integrated system". The different techniques required to observe regions that emit over very different parts of the electromagnetic spectrum (from the visible and infrared emission of the photosphere to the X-ray emission coming from active region cores and flare sites) make it rather non-trivial to follow disturbances and the flow of energy through the different atmospheric layers. However, it is becoming ever more evident that the capability of measuring energy release over the entire range of spatial, spectral, and temporal scales observed in different atmospheric regions is central for making further progress in such key areas as the heating of the Sun's upper atmosphere or the physics of solar flares and coronal mass ejections. These scales often differ markedly in the chromosphere, transition region, and corona. Currently, even the combination of data from several existing missions do not adequately cover the important scales. Combinations of data from different missions also tend to be restricted by difficulties in data co-registration and simultaneity. Since the magnetic field is the backbone of the solar corona, it is also necessary to measure it not only at the photosphere but also higher up, at least in the chromosphere, where the magnetic field starts dominating over the plasma. These measurements will greatly improve the extrapolation of the field into the corona and, together with high resolution spectroscopy and imaging of the plasma filling the magnetic structures, will produce fundamental advances in our understanding of how field and plasma processes form structures, how magnetic energy is released through instabilities, reconnection, wave dissipation, and particle acceleration, and what role the magnetic fields play in heating and accelerating plasma in the corona and the solar wind. Solar-C will be the first mission to reveal the spatial and temporal scales over which energy release in the solar atmosphere is aggregated into observable structures. Solar C is currently being proposed to JAXA for a launch in 2019 and detailed descriptions of the mission concept and of the proposed instruments are given in the Japanese Interim Report[1].

The basic characteristics of the three telescopes and of each instrument are summarized in Table 3. These instruments will provide overlapping temperature coverage and complementary capabilities such as spectroscopy and narrow wavelength band imaging, high cadence and throughput, and will feature fields-of-view large enough to properly study active regions. The 1.5m diameter main mirror of the SUVIT will make it comparable in size to the largest current ground-based solar telescopes and by far the largest solar instrument ever to fly in space.

The VUV spectrometer for this mission has been proposed to ESA as an European contribution. The proposal has received a positive evaluation by the ESA advisory structure. The spectrometer, named LEMUR in the proposal to ESA, is described by Teriaca et al. (2011).

[1] SOLAR-C Working Group, 2011, Interim Report on the SOLAR-C Plan-B Mission Concept. `http://hinode.nao.ac.jp/SOLAR-C/Documents/Interim2011/SC_plan-b.pdf`

Table 3. Solar-C instrumentation payload summary (extracted and adapted from Teriaca et al. 2011).

Instrument characteristic	Nominal value
	LEMUR/EUVST spectrometer
Telescope	30 cm diameter, off-axis paraboloid, f/12
Focal plane package	VUV single-grating spectrographs with visible light or UV slit imaging assembly
Wavelength coverage	170–212 Å, 695–845 Å, 925–1085 Å, 1110–1270 Å 2nd order 462–542 Å, 555–635 Å
Instantaneous field of view	$0.28'' \times 280''$ ($300'' \times 280''$ by rastering)
Spatial, temporal resolution	$0.28''$, ($0.14''$/pixel), down to 0.5 s (sit and stare)
Spectral resolution	$17000 \leq \lambda/\Delta\lambda \leq 32000$
	SUVIT (Solar UltraViolet, Visible, and Infrared Telescope)
Telescope	Ø 1.5 m (nominal), reflective, Gregorian telescope (f/9.54)
Focal plane package	Imaging and spectroscopic instrumentation, polarimetry
Wavelength coverage	He I 10830Å, D3 5876Å, Ca II 8542Å, 8498Å, Fe I 8538Å, Si I 10827Å, Mg II h/k 2800Å
Spatial, temporal resolution[1]	$\approx 0.1''$ ($0.05''$/pixel), 1 s
Field of view[2]	$\approx 200'' \times 200''$
	XIT (Extreme ultraviolet Imaging Telescope, normal incidence)[2]
Telescope type	Normal incidence EUV multilayer telescope, Ø 32 cm
Wavelength coverage	Multi-layer narrow bands centered at 94, 193, 304Å
Spatial and temporal resolution	$0.2''$ with $0.1''$/pixel, < 10 s
Field of view	$400'' \times 400''$

[1] Values refer to Narrow-band filtergrams at the shortest wavelengths. More complete and detailed information can be found in the Interim Report on the SOLAR-C Mission Concept.
[2] A $1''$ grazing incidence telescope with $0.5''$/pixel plate scale is also being considered. This telescope would include a photon counting detector with energy discrimination capability for spectroscopy.

5.3. ASPIICS

ASPIICS, which stands for Association de Satellites Pour l'Imagerie et l'Interfromtrie de la Couronne Solaire (Lamy et al. 2010) has been selected as the third keystone of ESA's technology demonstration program PROBA. Currently, a feasibility study is ongoing. It is the main goal of this mission to test the formation flight of a pair of spacecraft, such that the shadow of the leading spacecraft occults the aperture of the trailing spacecraft. This configuration is ideal to place a telescope on the trailing spacecraft which will work as an externally occulted coronagraph, with the leading spacecraft forming the occulter. The intersatellite distance will be 150 m, which corresponds to a nominal occultation down to 1.02 solar radii. Thanks to the formation flying technology this powerful coronagraph will have a good resolution very close to the Sun, which has never been accomplished before. ASPIICS will be designed as a white-light filtergraph. In visible light the disk outshines the corona by six orders of magnitude. Still, ASPIICS will be able to observe very faint phenomena in the solar corona due to the extremely reduced levels of scattered light from the disk that is a limiting factor for disk imagers. The consortium, with contributions from Belgium, Czech Republic, France, Germany, Greece, Russia and Switzerland is working for a launch in 2015.

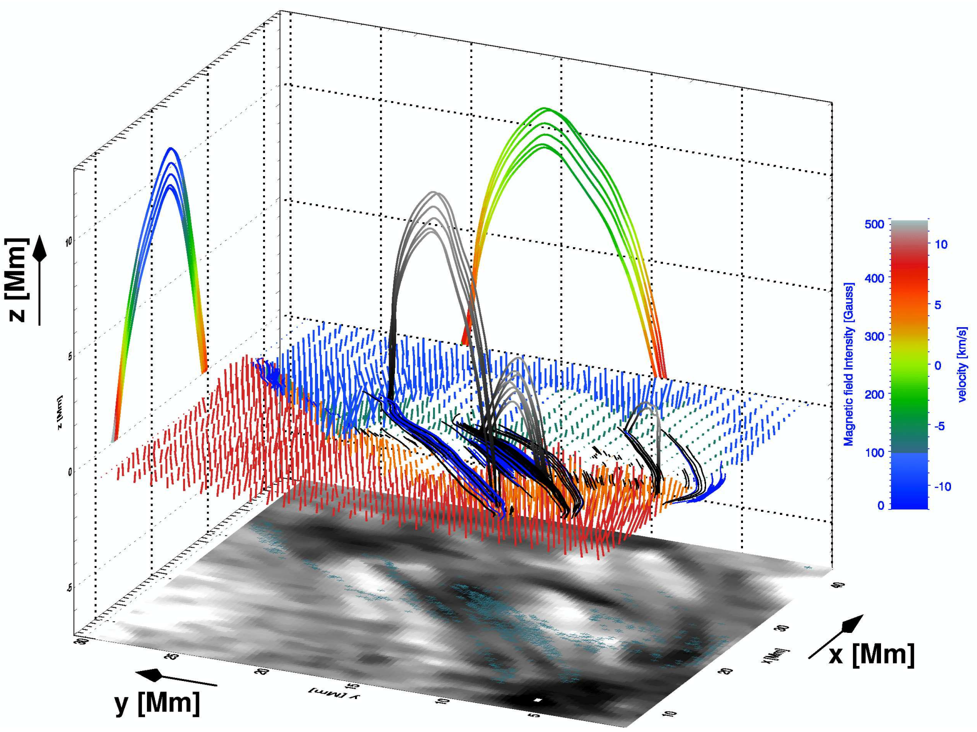

Fig. 13. Freshly emerged and rising magnetic loops reconstructed from Stokes vector data in the upper chromospheric He I line. The maps at the bottom show the magnetic polarity and connectivity (in colour) and the equivalent width of the He I triplet. The plotted representative field lines for one of the reconstructed loops are projected onto the x–z and y–z planes. The colour-coding of the loop projections represents the vertical velocity (y–z plane) and the magnetic field strength (x–z plane). The loops are rooted in areas with downflowing material, while in the apex upflowing material is observed. From Solanki et al. (2003)
.

6. Ground-based facilities

Just as in studies of the night sky, there is a firm place for telescopes observing the Sun from the ground, for the reasons listed in Sect. 1. There are too many ground-based observatories to discuss them all, even the European ones. Many of these are national observatories that do either routine or highly specialized work (such as providing synoptic data, e.g. sunspot counts, full-disk Hα or other images, or for testing new techniques and instruments). An example of a successful synoptic telescope is the PSPT operating in Rome and regularly imaging the full solar disk for well over a decade in multiple wavelength bands which are important for solar irradiance modeling (Ermolli et al. 1998). Only those having a broader significance are introduced below (both the presently working ones and the ones planned for the future).

The largest collection of solar telescopes worldwide is found on the two Canary Islands Tenerife and La Palma, which were chosen for their outstanding seeing conditions. Currently there are 5 major solar telescopes there, two built and operated by Germany (VTT, Gregor, see Schmidt et al. 2012a), one by Sweden (SST, see Scharmer et al. 1999), one by the Netherlands (DOT; Dutch Open Telescope, see Hammerschlag & Bettonvil 1998; Rutten et al. 2002) and one built jointly by France and Italy (Themis, see Arnaud et al. 1998). In addition, smaller telescopes running, e.g., as part of global helioseismology networks are also located on Tenerife, i.e. instruments that are part of the BiSON (Birmingham Solar Oscillations Network) and of the GONG (Global Oscillations Network Group) networks.

The scientifically most successful of the major telescopes have been the VTT (Vacuum Tower Telescope) on Tenerife and the SST (Swedish Solar Telescope) on La Palma. The former, commissioned in 1985, has a primary mirror with a diameter of 70cm, the latter, which is observing since 2002, has an approximately 1 meter primary lens. Each of these telescopes has multiple user instruments. The most used instruments on the VTT are the upgraded Tenerife Infrared Polarimeter, TIP-II (Collados et al. 2007), the Göttingen Fabry Perot Interferometer, GFPI (Puschmann et al. 2006), and the spectropolarimeter, POLIS (Schmidt et al. 2003).

Selected highlights from the VTT are the measurement of truly weak fields by making use of the large Zeeman sensitivity in the infrared by Khomenko et al. (2003), the first map of the vector magnetic field in the upper chromosphere, allowing the magnetic field to be followed along young magnetic loops and leading to the discovery of the first electric current sheet in the solar atmosphere (Solanki et al. 2003), see Fig. 13, and the successful modelling of a chromospheric profile observed by TIP-II (Trujillo Bueno et al. 2002).

The main instrument at the SST (Scharmer et al. 2003) is the Fabry Perot interferometer CRISP, although a lot of excellent science has also been done using a broad-band imager. This telescope and its predecessor in the same building, the SVST with a 50 cm diameter main lens, have regularly provided data with outstanding spatial resolution. Two of the main results from the SST have been the discovery of dark cores in penumbral filaments (Scharmer et al. 2002) and the discovery of cool downflows in the inner penumbrae of sunspots suggestive of overturning convection (Joshi et al. 2011; Scharmer et al. 2011).

IBIS (Interferometric BIdimensional Spectrometer) is a Fabry-Perot based instrument capable of performing high spatial resolution, rapid imaging spectroscopy and polarimetry of the solar photosphere and chromosphere (Cavallini 2006; Reardon & Cavallini 2008). IBIS was designed and built at the Arcetri Astrophysical Observatory (INAF) with contributions from the Universities of Florence and Rome Tor Vergata, and is currently operating as facility instrument at the Dunn Solar Solar Telescope of the US National Solar Observatory. IBIS offers diffraction-limited imaging (Righini et al. 2010) with high spectral resolution (R $\geq$ 200,000), over the largest field-of-view for a solar imaging spectrometer (95′ diameter). Full-Stokes spectropolarimetric measurements are routinely performed, employing a dual-beam setup, with an achievable polarimetric accuracy of better than 3×10^{-3}, limited by photon counts (e.g. Viticchié et al. 2010). IBIS has pioneered the use of the CaII 854.2 nm line over large fields of view as a powerful diagnostics of chromospheric dynamics (Cauzzi et al. 2008). Evidence of shock-driven turbulence in the quiet chromosphere (Reardon et al. 2008) and of "aureolas" of enhanced chromospheric temperature around network elements (Cauzzi et al. 2009) has been obtained exploiting this diagnostics. Important results on the nature of wave propagation through the atmosphere have arisen by sampling in rapid succession spectral lines formed at different heights. Highlights include, e.g., the development of acoustic shocks in the quiet chromosphere (Vecchio et al. 2009), the role of magnetic elements on wave transmission and conversion (Vecchio et al. 2007; Stangalini et al. 2011; Jess et al. 2012), the presence and role of atmospheric gravity waves (Straus et al. 2008). Finally, the dynamics and structure of fine photospheric and chromospheric magnetic elements have been studied in a variety of situations, from moving magnetic features around decaying spots (Zuccarello et al. 2009), to magnetic bright points (Romano et al. 2012), to the topology of chromospheric fibrils (Reardon et al. 2011).

Of all the telescopes operating on the Canary Islands, the aesthetically most pleasing to the eye is Themis (Arnaud et al 1998). This telescope was also the first major solar telescope to be designed to be polarization free. An important instrument is the Multi Channel Subtractive Double Pass instrument (MSDP), see Mein (2002), which allows spectra to be obtained over a two-dimensional area simultaneously.

Very recently the 1.5m diameter Gregor telescope (Schmidt et al. 2012b) has seen first light and scientific observations are expected to start in 2013. This is the largest solar telescope on European soil and first images look very promising. The two main initial scientific instruments are the GRIS (Collados & et al. 2012), a grating spectrometer to be run together with TIP-II, and the Gregor Fabry-Perot Interferometer (GFPI); see Puschmann & et al. (2012).

The main project for the future of European ground-based solar physics is the EST (European Solar Telescope), see Collados (2008), which will be a 4-m class optical telescope to be located on the Canary Islands. It will be equipped with state-of-the-art instruments and will have similar dimensions as its American counterpart, the ATST (Advanced Technology Solar Telescope), see Keil et al. (2003) that is being built on Hawaii. The EST will be complementary to the ATST. Whereas the ATST will be an outstanding all-round telescope, the EST will concentrate more strongly on accurate and sensitive polarimetry at the highest spatial resolution possible, which is of utmost importance for making advances in the study of solar magnetism. The telescope's large diameter will also provide ample flux, needed by photon starved observations of the solar magnetic field in quiet Sun regions. A telescope of this dimension will lead to very significant advances thanks to its size, high-quality instrumentation and advances in adaptive optics systems.

Besides these dedicated telescopes, the solar radio community profits from being able to employ general purpose radio telescopes. Particularly important developments have been the LOFAR (LOw Frequency ARray) project as well as ALMA (Atacama Large Millimeter Array). The latter, once solar observations are allowed, will open a new window on the solar chromosphere that will be competitive in its spatial rsolution and unique in its temperature sensitivity (sensing both the cold and the hot gas in the highly inhomogeneous solar chromosphere).

7. Summary

In this paper we have given an overview of the European solar missions and observatories now working, under construction or planned. The operating solar missions and telescopes have had a huge impact on our knowledge of the Sun and have completely revised our understanding of many solar phenomena. The charge has been led by ESA's first cornerstone mission, SOHO, which transformed our image of the Sun from a relatively static system, to a highly dynamic one. Subsequent missions and observations have highlighted and filled in this new picture even further and revealed additional, finer and more dynamic and variable structures on the Sun. Of particular importance for future solar physics, both in Europe and internationally, will be Solar Orbiter, a mission that will go close to the Sun, probe the coupling within the solar atmosphere and between it and the solar wind. It will also for the first time image the solar poles from an out-of-ecliptic vantage point. Beyond that the Japanese-led international Solar-C mission will be a major focal point for European solar physics. Important new instruments are also expected to start operating on ground-based telescopes, in particular on the just completed Gregor telescope and later on the large European Solar Telescope (EST). In summary, we are living in a golden age of solar physics which was kicked off by the launch of SOHO. Since then progress has accelerated and more highlights and discoveries are expected as new missions and telescopes start delivering unique data.

Acknowledgements. This work has been partially supported by the WCU grant (No. R31-10016) funded by the Korean Ministry of Education, Science and Technology. It also benefited from material provided by ESA and NASA for education and public relation purposes. We thank the Editors for carefully reading the manuscript and for helpful comments.

References

Antonucci, E., Abbo, L., & Telloni, D. 2011, Space Sci. Rev., 96

Arnaud, J., Mein, P., & Rayrole, J. 1998, in ESA Special Publication, Vol. 417, Crossroads for European Solar and Heliospheric Physics. Recent Achievements and Future Mission Possibilities, 213

Aschwanden, M. J. 2011, Living Reviews in Solar Physics, 8, 5

Ball, W. T., et al. 2012, A&A, 541, A27

Barthol, P., et al. 2011, Sol. Phys., 268, 1

Bello González, N., et al. 2010, ApJ, 723, L134

Bemporad, A., Poletto, G., Raymond, J. C., et al. 2005, ApJ, 620, 523

Benmoussa, A., et al. 2009, A&A, 508, 1085

Berghmans, D., et al. 2006, Advances in Space Research, 38, 1807

Berkefeld, T., et al. 2011, Sol. Phys., 268, 103

Bertaux, J. L., et al. 1995, Sol. Phys., 162, 403

Bonet, J. A., et al. 2010, ApJ, 723, L139

Borrero, J. M., et al. 2010, ApJ, 723, L144

Brooks, D. H. & Warren, H. P. 2011, ApJ, 727, L13

Brueckner, G. E., et al. 1995, Sol. Phys., 162, 357

Bryans, P., Young, P. R., & Doschek, G. A. 2010, ApJ, 715, 1012

Cauzzi, G., et al. 2009, A&A, 503, 577

Cauzzi, G., et al. 2008, A&A, 480, 515

Cavallini, F. 2006, Sol. Phys., 236, 415

Cheung, M. C. M., Schüssler, M., Tarbell, T. D., & Title, A. M. 2008, ApJ, 687, 1373

Cirtain, J. W., Golub, L., Lundquist, L., & et al. 2007, Science, 318, 1580

Collados, M. 2008, in European Solar Physics Meeting, Vol. 12, European Solar Physics Meeting, ed. H. Peter, 6

Collados, M. & et al. 2012, Astron. Notes, 333, 872

Collados, M., Lagg, A., Díaz Garcí A, J. J., et al. 2007, in Astronomical Society of the Pacific Conference Series, Vol. 368, The Physics of Chromospheric Plasmas, ed. P. Heinzel, I. Dorotovič, & R. J. Rutten, 611

Cranmer, S. R., Kohl, J. L., Noci, G., et al. 1999, ApJ, 511, 481

Culhane, J. L., et al. 2007, Sol. Phys., 243, 19

Danilovic, S., et al. 2010a, ApJ, 723, L149

Danilovic, S., Schüssler, M., & Solanki, S. K. 2010b, A&A, 513, A1

de Patoul, J., Inhester, B., Feng, L., & Wiegelmann, T. 2011, Sol. Phys., 415

Delaboudinière, J.-P., et al. 1995, Sol. Phys., 162, 291

Dewitte, S., Crommelynck, D., Mekaoui, S., & Joukoff, A. 2004, Sol. Phys., 224, 209

Domingo, V., et al. 2009, Space Sci. Rev., 145, 337

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

Doschek, G. A., et al. 2008, ApJ, 686, 1362

Ermolli, I., et al. 1998, Sol. Phys., 177, 1

Feng, L., et al. 2012, ApJ, 751, 18

Fröhlich, C. 2006, Space Sci. Rev., 125, 53

Fröhlich, C. 2009, A&A, 501, L27

Fröhlich, C., et al. 1995, Sol. Phys., 162, 101

Gabriel, A. H., et al. 1995, Sol. Phys., 162, 61

Gandorfer, A., et al. 2011a, Sol. Phys., 268, 35

Gandorfer, A., et al. 2011b, Journal of Physics Conference Series, 271, 012086

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

Habbal, S. R., et al. 2011, ApJ, 734, 120

Halain, J.-P., et al. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, (in press), Vol. 8443, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series

Hammerschlag, R. H. & Bettonvil, F. C. M. 1998, New Astronomy Review, 42, 485

Harra, L. K., et al. 2008, ApJ, 676, L147

Harrison, R. A., et al. 1995, Sol. Phys., 162, 233

Hassler, D. M., et al. 1999, Science, 283, 810

Hirzberger, J., et al. 2010, ApJ, 723, L154

Hochedez, J.-F., et al. 2006, Advances in Space Research, 37, 303

Hovestadt, D., et al. 1995, Sol. Phys., 162, 441

Howard, R. A., et al. 2008, Space Sci. Rev., 136, 67

Howard, T. A. & DeForest, C. E. 2012, ApJ, 746, 64

Jess, D. B., et al. 2012, ApJ, 757, 160

Joshi, J., et al. 2011, ApJ, 734, L18

Kaiser, M. L., et al. 2008, Space Sci. Rev., 136, 5
Keil, S. L., et al. 2003, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4853, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. S. L. Keil & S. V. Avakyan, 240–251
Khomenko, E. V., et al. 2003, A&A, 408, 1115
Kienreich, I. W., et al. 2012, ArXiv e-prints
Kohl, J. L., et al. 1995, Sol. Phys., 162, 313
Kohl, J. L., Noci, G., Cranmer, S. R., & Raymond, J. C. 2006, A&A Rev., 13, 31
Kosugi, T., et al. 2007, Sol. Phys., 243, 3
Krieger, A. S., Timothy, A. F., & Roelof, E. C. 1973, Sol. Phys., 29, 505
Krivova, N. A., Solanki, S. K., Fligge, M., & Unruh, Y. C. 2003, A&A, 399, L1
Lagg, A., et al. 2010, ApJ, 723, L164
Lamy, P., Damé, L., Vivès, S., & Zhukov, A. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7731, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Lin, R. P., et al. 2002, Sol. Phys., 210, 3
Lites, B. W., et al. 2008, ApJ, 672, 1237
Lugaz, N., et al. 2012, Sol. Phys., 279, 497
Maloney, S. A. & Gallagher, P. T. 2011, ApJ, 736, L5
Martínez González, M. J., et al. 2011, ApJ, 730, L37
Martínez González, M. J., et al. 2012, ArXiv e-prints
Martínez Pillet, V., et al. 2011, Sol. Phys., 268, 57
Mein, P. 2002, A&A, 381, 271
Mierla, M., et al. 2010, Annales Geophysicae, 28, 203
Mierla, M., et al. 2012, Sol. Phys., 66
Moreno-Insertis, F., Galsgaard, K., & Ugarte-Urra, I. 2008, ApJ, 673, L211
Müller-Mellin, R., et al. 1995, Sol. Phys., 162, 483
Orozco Suárez, D., et al. 2007, ApJ, 670, L61
Pasachoff, J. M., et al. 2011, ApJ, 734, 114
Pesnell, W. D., Thompson, B. J., & Chamberlin, P. C. 2012, Sol. Phys., 275, 3
Puschmann, K. & et al. 2012, Astron. Notes, 333, 880
Puschmann, K. G., Kneer, F., Seelemann, T., & Wittmann, A. D. 2006, A&A, 451, 1151
Raouafi, N.-E. & Solanki, S. K. 2004, A&A, 427, 725
Raouafi, N.-E. & Solanki, S. K. 2006, A&A, 445, 735
Reardon, K. P. & Cavallini, F. 2008, A&A, 481, 897
Reardon, K. P., Lepreti, F., Carbone, V., & Vecchio, A. 2008, ApJ, 683, L207
Reardon, K. P., Wang, Y.-M., Muglach, K., & Warren, H. P. 2011, ApJ, 742, 119
Riethmüller, T. L., et al. 2010, ApJ, 723, L169
Righini, A., Cavallini, F., & Reardon, K. P. 2010, A&A, 515, A85
Romano, P., et al. 2012, Sol. Phys., 280, 407
Rutten, R. J., et al. 2002, in ESA Special Publication, Vol. 506, Solar Variability: From Core to Outer Frontiers, ed. A. Wilson, 903–906
Sakao, T., et al. 2007, Science, 318, 1585
Scharmer, G., Owner-Petersen, M., Korhonen, T., & Title, A. 1999, in Astronomical Society of the Pacific Conference Series, Vol. 183, High Resolution Solar Physics: Theory, Observations, and Techniques, ed. T. R. Rimmele, K. S. Balasubramaniam, & R. R. Radick, 157
Scharmer, G. B., Bjelksjo, K., Korhonen, T. K., Lindberg, B., & Petterson, B. 2003, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 4853, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. S. L. Keil & S. V. Avakyan, 341–350
Scharmer, G. B., et al. 2002, Nature, 420, 151
Scharmer, G. B., Henriques, V. M. J., Kiselman, D., & de la Cruz Rodríguez, J. 2011, Science, 333, 316
Scherrer, P. H., et al. 1995, Sol. Phys., 162, 129
Schmidt, W., Beck, C., Kentischer, T., Elmore, D., & Lites, B. 2003, Astronomische Nachrichten, 324, 300
Schmidt, W., , et al. 2012a, Astronomische Nachrichten, 333, 796
Schmidt, W., et al. 2012b, Astron. Notes, 333, 796
Schrijver, C. J. & De Rosa, M. L. 2003,

Sol. Phys., 212, 165
Schühle, U., Halain, J.-P., Meining, S., & Teriaca, L. 2011, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8148, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series
Schüssler, M. & Vögler, A. 2008, A&A, 481, L5
Seaton, D. B., et al. 2012, ArXiv e-prints
Sekanina, Z. 2002, ApJ, 566, 577
Solanki, S. K., et al. 2010, ApJ, 723, L127
Solanki, S. K., et al. 2003, Nature, 425, 692
Stangalini, M., Del Moro, D., Berrilli, F., & Jefferies, S. M. 2011, A&A, 534, A65
Steiner, O., et al. 2010, ApJ, 723, L180
Steiner, O., Rezaei, R., Schaffenberger, W., & Wedemeyer-Böhm, S. 2008, ApJ, 680, L85
Stenflo, J. O. 1973, Sol. Phys., 32, 41
Straus, T., Fleck, B., Jefferies, S. M., et al. 2008, ApJ, 681, L125
Temmer, M., Rollett, T., Möstl, C., et al. 2011, ApJ, 743, 101
Teriaca, L., et al. 2011, Experimental Astronomy, 135
Torsti, J., et al. 1995, Sol. Phys., 162, 505
Trujillo Bueno, J., et al. 2002, Nature, 415, 403
Tsuneta, S., et al. 2008, Sol. Phys., 249, 167
Tu, C.-Y., et al. 2005, Science, 308, 519
Usoskin, I. G., Solanki, S. K., & Kovaltsov, G. A. 2007, A&A, 471, 301
Van Doorsselaere, T., et al. 2011, ApJ, 740, 90
van Noort, M. 2012, ArXiv e-prints
Vecchio, A., Cauzzi, G., & Reardon, K. P. 2009, A&A, 494, 269
Vecchio, A., et al. 2007, A&A, 461, L1
Viticchié, B., Del Moro, D., Criscuoli, S., & Berrilli, F. 2010, ApJ, 723, 787
Webb, D. F. & Howard, T. A. 2012, Living Reviews in Solar Physics, 9, 3
Wenzler, T., Solanki, S. K., & Krivova, N. A. 2009, Geophys. Res. Lett., 36, 11102
Wiegelmann, T., et al. 2010, ApJ, 723, L185
Wilhelm, K., et al. 2011, Astron. Astrophys. Rev., 19
Wilhelm, K., et al. 1995, Sol. Phys., 162, 189
Woch, J., et al. 1997, Geophys. Res. Lett., 24, 2885
Yokoyama, T. & Shibata, K. 1995, Nature, 375, 42
Zuccarello, F., et al. 2009, A&A, 500, L5