Solar observations from space and from the ground

W. CURDT

Max-Planck-Institut für Aeronomie, 37191 Katlenburg-Lindau

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Abstract. Recent results from space missions like *YOHKOH*, *SOHO* or *TRACE* as well as ground-based observations clearly indicate that physical processes of most solar phenomena take place on small scales, which are still below the resolution of the instruments employed. There is an urgent need for observations at higher resolution and also for their extension to multi-wavelength regimes. Space-borne as well as ground-based instruments have limitations of the present-day technology, although in a different way. In this communication, an overview of space instruments currently in operation or in the preparation phase is presented and references to more detailed information are given.

Key words: Sun: space instrumentation

1. Introduction

Space astronomy started in 1946 in the United States when W. von Braun's A4 rocket engines (during war named V-2 missile) became available to scientists for launching free-flying, high-altitude observatories carrying spectrometers, imagers, coronagraphs or in-situ instruments for the detection of charged particles over a wide energy range. Since then much progress has been made in solar and stellar observational techniques from space.

By observations from space new wavelength regimes became accessible. Therefore EUV and X-ray instrumentation as well as in-situ instruments for particle detection have primarily been chosen to equip previous space projects. This group includes the *OSO* armada, *Skylab ATM*, *Helios* 1&2, *SMM*, *Hinotori*, *Coronas-I*, and the highly successful *YOHKOH* mission (Antiochus et al. 1997), which stopped operations only recently. The radio, infrared and optical wavelength range is still the domain of ground-based observatories. Enormous progress has also been made in this area and new technologies are available to overcome atmospheric problems. However, this review will focus on space projects, thus complementing other contributions to this volume.

Numerous dedicated smaller instruments were or will be put up into space. They can not be included in this review. Also, those missions are not covered, which are not yet fully approved, e.g. *ASCE* or *Solar Probe*.

Correspondence to: curdt@linmpi.mpg.de

2. Space Missions in operation

Ongoing solar space missions are listed in Table 1 together with references to more detailed information available on the internet.

The *Ulysses* scientific investigations encompass studies of the heliospheric magnetic field, heliospheric radio and plasma waves, the solar wind plasma, solar and interplanetary energetic particles and cosmic rays (Wenzel et al. 1992). It also carries radio science instruments to probe the solar corona and instruments to study cosmic dust, interstellar neutral gas, and gravitational waves. *Ulysses* was injected into an interplanetary out-of-ecliptic orbit with perihelion passages over the Sun's poles. While the first polar passes in 1994 and 1995 occurred during solar minimum, the second orbit happened during the maximum of solar cycle 23 with polar passes in 2000 and 2001.

SOHO, the **SO**lar and **H**eliospheric **O**bservatory of ESA and NASA carries on board a suite of powerful coronal instruments as well as an in-situ package (Domingo et al. 1995). These include helioseismology instruments (MDI-SOI, GOLF), EUV- and VUV spectrometers (CDS, SUMER), a EUV full-disk imager (EIT), a magnetic imager (MDI), white-light and VUV coronagraphs (LASCO, UVCS), the SWAN hydrogen absorption cell instrument, the VIRGO global-Sun radiometer, and the in-situ particle instruments CELIAS, COSTEP and ERNE. *SOHO* orbits around the Lagrangian point, L_1, and, in constant view of the Sun, returns since 1996 (with a short interruption in 1998) continuously a flood of scientific data.

Table 1. Space missions currently in operation

Mission	Short description	Web address
Ulysses	Deep-space mission over the Sun's poles	http://helio.estec.esa.nl/ulysses/mission.html
SOHO	SOlar and Heliospheric Observatory	http://sohowww.nascom.nasa.gov/
TRACE	Transition Region and Coronal Explorer	http://sunland.gsfc.nasa.gov/smex/trace/
ACE	Advanced Composition Explorer	http://www.srl.caltech.edu/ace/
Genesis	Solar wind collecting spacecraft	http://www.genesismission.org/mission/index.html
Coronas-F	Flare mission with EUV and soft x-ray instruments	http://charley.izmiran.rssi.ru/projects/coronas/f/coronas-f.html
RHESSI	High energy spectroscopic imager	http://hesperia.gsfc.nasa.gov/hessi/

The nominal *SOHO* operational phase of at least two years and an optional extension of another four years will end in 2003. However, with all instruments on board still functioning, ESA and NASA have decided to extend the successful mission now titled "The Solar Cycle Mission" until 2007. This will allow sufficient overlap with the new undertakings at the horizon and opens the option of co-observation and the possibility of cross-calibration.

TRACE is a NASA SMEX (**SM**all **EX**plorer) mission for high-resolution imaging of the upper solar atmosphere, launched and injected into an Sun-synchronous polar orbit in April 1998 (cf., Fig.1). Its 30-cm aperture Cassegrain telescope feeds a multi-layer optic with small-bandpass filters tuned at 171 Å (Fe IX/X), 195 Å (Fe XII), 284 Å (Fe XV), 1216 Å (H I Lyα), 1550 Å, 1600 Å, and 1700 Å. With 0.5 arcsec pixels and a temporal resolution down to 1 s, *TRACE* can take images and breath-taking movies of solar plasmas emitting at different formation temperatures (Schrijver 1996).

NASA's Advanced Composition Explorer, *ACE*, is orbiting the first Lagrangian point L_1 since 1997, where it continuously probes accelerated particles over a wide energy range, arriving not only from the Sun, but also from interstellar and galactic sources. It is equipped with six high-resolution sensors and three monitoring instruments, which allow comprehensive determinations of the elemental, isotopic, and ionic charge state composition and energy measurements from 100 eV/nucleon to 500 MeV/nucleon for elements with atomic numbers Z up to 30, from hydrogen to zinc (Stone et al. 1998).

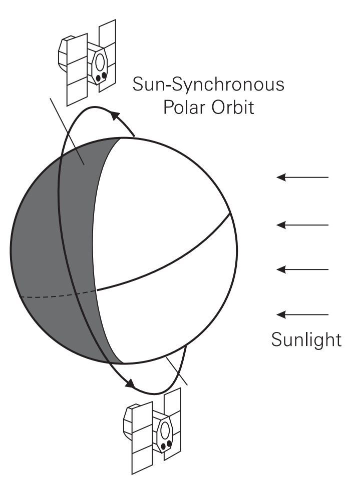

Fig. 1. Spacecraft observing from a Sun-synchronous polar orbit

The *Genesis* spacecraft travelled beyond the magnetic influence of Earth, and has been collecting solar wind particles by ion implantation into the collector materials since 2001. Both instruments on board, the collector and the ion concentrator contain ultra-high purity target materials, each of which is tailored to enable the analysis of a different family of elements. After a two years exposure, the deployed targets will be folded up and put into a sealed canister. A re-entry capsule will finally return them to Earth for laboratory analysis (Wiens et al. 2002). These samples will allow precise measuring of solar elemental abundances of oxygen, nitrogen, and noble gases and thus enable scientists to better understand the isotopic variations in meteorites, comets, lunar samples, and planetary atmospheres.

The Russian *Coronas-F* satellite carries a cluster of scientific instruments to study the UV-, X-ray, gamma and radio emission of the active or flaring Sun. It is equipped with high-resolution small-band X-ray imagers as well as X-ray spectrometers and X-ray radiometers and observes the Sun from an Earth orbit since 2001 (Oraevsky 2002).

The High Energy Spectroscopic Imager, *RHESSI*, is a NASA SMEX mission. Since February 2002, it observes solar but also stellar targets in order to explore the impulsive energy release of the corona. Its instrumentation will allow to study the physics of particle acceleration in flares and the heating of plasmas to tens of millions of degrees, and to determine the relative abundances of accelerated and ambient ions in flares (Lin 2002).

3. Space Missions in preparation

A detailed review of the prospects of future space missions is given by Fleck (2002). In this section the scientific goals and the instrumentation of the missions *Solar-B*, *Stereo*, *Sunrise*, *SDO*, and *Solar Orbiter* will be described.

3.1. *Solar-B* Scientific Goals and Instrumentation

Solar-B is a mission led by ISAS, the Japanese space agency, with major contributions of LMSAL, SAO, and MSSL to be launched in 2005. The mission can be understood as a follow-on to the highly successful *YOHKOH* mission. Its scientific goal is to advance our understanding of the origin of the outer solar atmosphere, the corona, and of the coupling between the fine magnetic structure at the photosphere and the dynamic processes occurring in the corona.

Table 2. Space missions in preparation

Mission	Instrumentation	Short description	Scheduled launch
Solar B	SOT	50 cm optical telescope (150 km resolution)	August 2005
	FPP	narrow-band filtergrams/magnetograms/Dopplergrams/Stokes images	
	XRT	full-disk X-ray imager (2 Å to 60 Å), *YOHKOH*-SXT follow-on	
	EIS	multi-layer EUV telescope/spectroscope (170 - 210 Å and 250-290 Å)	
Stereo	SECCHI	2 white-light coronagraphs/EUV imager/heliosperic imager	November 2005
	SWAVES	interplanetary radio burst tracker	
	IMPACT	in-situ solar energetic particle detector	
	PLASTIC	plasma and suprathermal ion detector	
Sunrise	SUPOS	spectro-polarimeter	January 2007
	SUFI	UV and optical filtergraph	
	IMAX	magnetograph	
SDO	HMI	helioseismic and magnetic imager (MDI follow-on)	August 2007
	SHARPP	white-light coronographic imager	
	EVE	full-disk irradiance spectrometer (10-1200 Å)	
SOLO	VIM	white-light imager & magnetograph	2011-2012
	EUS	EUV spectrometer	
	EUI	EUV imager	
	UVC	UV & white-light coronagraph	
	SWA/RPW	solar wind plasma analyser / radio & plasma waves analyser	
	CRS/RAD	coronal radio sounding/radiometer	
	MAG	magnetometer	
	EPD/NED	energetic particle detector / neutron detector	
	DUD/NPD	dust detector / neutral particle detector	

The *Solar-B* payload comprises three instruments. A 50-cm aperture diffraction-limited optical telescope will allow solar observations at 150 km resolution (SOT). The telescope feeds a focal-plane package (FPP) designed for photospheric and chromospheric imaging and spectropolarimetry. The images will be stabilized to better than 0.02 arcsec by an active high-speed correlation-tracking system.

Solar-B will also carry a full-disk **X**-**R**ay **T**elescope observing from 2 to 60 Å (XRT). XRT is a grazing-incidence modified Wolter I telescope with 35 cm aperture. It is an enhanced version of the SXT instrument on *YOHKOH* with a spatial resolution of 1 arcsec and a broader coverage of formation temperatures.

The **E**UV **I**maging **S**pectrograph (EIS), observing in two channels, consists of a 15-cm aperture multilayer-coated telescope and a toroidal-grating spectrometer. EIS will have spatial resolution elements of 1 arcsec and spectral resolution elements, which can be converted to Doppler-flows of $\pm$ 3 km/s. Half of each optic is coated differently, thus optimized for transmission in the 170 to 210 Å channel or in the 250 to 290 Å channel.

3.2. *Stereo* Scientific Goals and Instrumentation

Stereo is a NASA led mission with international contribution to be launched in 2005. It will consist of two identical spacecraft in stereoscopic view of the Sun. Its scientific goal is the investigation of the origin of CMEs and their consequences.

Onboard of both spacecraft will be an identical suite of remote-sensing and in-situ instruments, which includes a unit consisting of two white-light coronagraphs, a full Sun EUV imager, and a heliospheric imager for observations of the heliosphere from 12 $R_\odot$ to beyond Earths orbit (SECCHI). *Stereo* will also carry an interplanetary radio burst tracker (SWAVES), which will trace the generation and evolution of travelling radio disturbances from the Sun to the orbit of the Earth. The **I**n-situ **M**easurements of **PA**rticles and **C**ME **T**ransients (IMPACT) investigation will measure the 3-D distribution and plasma characteristics of energetic particles and local vector magnetic field. The **PLA**sma and **S**upra **T**hermal **I**on and **C**omposition experiment (PLASTIC) will provide plasma characteristics of protons, alpha particles, and heavy ions.

3.3. *Sunrise* Scientific Goals and Instrumentation

Sunrise is a suborbital mission of the German space agency with international contribution to be launched in 2007. A balloon-borne light-weight 1-m telescope will feed a suite of focal-plane instruments. *Sunrise* will, for the first time, provide measurements of the magnetic structure of the solar atmosphere on its intrinsic spatial and temporal scales (Schmidt et al. 2001). These measurements will directly attack basic problems:

– What are the origin and the properties of the intermittent magnetic structure?
– How is the magnetic field brought to and removed from the solar surface?
– How does the field provide momentum and energy for the outer solar atmosphere?
– How does the magnetic field variation modify the solar brightness?

At least two flights over Antarctica are foreseen for *Sunrise*. On the long term, this mission could develop into a large-telescope space mission.

The **SU**nrise **S**pectro-**PO**larimeter (SUPOS) will measure spectral line profiles in all four Stokes parameters. With *Sunrise*, the observable wavelength range extends well into the UV and permits spectroscopy of the Mg II K line core at 2796 Å. The UV and optical filtergraph (SUFI) is designed as a multi-wavelength slit-jaw camera of SUPOS. Three wavelengths each are chosen to sample the photosphere and chromosphere. The Imaging Magnetograph Experiment (IMAX) is an imaging vector magnetograph based upon narrow-band filters. It will provide high-cadence 2-D maps of the complete magnetic vector and the line-of-sight velocity with high spatial resolution.

3.4. *SDO* Scientific Goals and Instrumentation

The **S**olar **D**ynamics **O**bservatory, *SDO*, is the first cornerstone of NASA's **I**nternational **L**iving-**W**ith-a-**S**tar programme (ILWS) to be launched in 2007. Its scientific goals are to understand, ideally to the point of predictability, the solar variations that influence life on Earth and humanity's technological systems by determining how the Sun's magnetic field is generated and structured and how this stored magnetic energy is converted and released into the heliosphere and geospace in the form of solar wind, energetic particles, and variations in solar irradiance.

Three instruments have been selected from the proposals invited by the NASA **A**nnouncement of **O**pportunity. The **H**elioseismic and **M**agnetic **I**mager (HMI) is a follow-on version of the MDI instrument on *SOHO*. The **S**olar **H**eliospheric **A**ctivity **R**esearch and **P**rediction **P**rogramme (SHARPP) is an advanced version of the LASCO instrument on *SOHO*. The **E**xtreme-ultraviolet **V**ariability **E**xperiment (EVE) is an irradiance spectrometer operating in the spectral range from 10 Å to 1200 Å. It will provide continuous observations of the full-disk solar irradiance that causes variation in composition, density, and temperature of the Earth's ionosphere and thermosphere.

3.5. *Solar Orbiter* Scientific Goals and Instrumentation

In 2000, the **SOL***ar* **O***rbiter* (SOLO) was selected as an ESA near-Sun mission with international contribution. It was reconfirmed by the SPC in May 2002. The key mission feature of *SOLO* is to study the Sun from close-up (45 solar radii) in an orbit tuned to solar rotation in order to examine the solar surface and the space above from a co-rotating vantage point at high spatial resolution, and to provide images of the Sun's polar regions from heliographic latitudes as high as 38 degrees. This part of the inner heliosphere is almost unexplored and therefore, unique in-situ measurements will be possible as well as close-up out-of-the-ecliptic observations of the solar atmosphere. To reach its novel orbit, *SOLO* will make use of low-thrust solar electric propulsion interleaved by Earth and Venus gravity assist. The strawman payload considered in the assessment study (Marsch et al. 2000) encompasses a package of heliospheric instruments and a group of remote-sensing instruments.

ESA has established two Solar Orbiter working groups to harmonize the definition and the implementation of the scientific payload presently foreseen. The coronal remote-sensing instrumentation consists of a full-disk EUV imager with high resolution, a high-performance EUV spectrometer, a full-disk visible-light telescope and magnetograph, EUV and visible-light coronagraphs, and a radiometer.

The heliospheric instrument package consists of a solar wind plasma analyser, a radio and plasma waves analyser, a magnetometer, energetic particle detectors, an interplanetary dust detector, and detectors for neutral particles and solar neutrons.

4. Space observations and ground observations

The complementary nature of space missions and ground-based projects is obvious. Free-flying spacecraft can observe the Sun independently from weather conditions and free off atmospheric disturbances and pointing jitter (provided they are unmanned). Sun-synchronous polar orbits or halo orbits around the first Lagrangian point L_1 allow long-term studies requiring an uninterrupted view of the Sun. Also, the lack of atmospheric extinction opens new spectral windows to solar observers. On the other hand, the costs of space missions can be enormous, the lifetime of the hardware in space and the on-board resources are limited, and the technology of the equipment is often more than 10 years old. These facts lead to unexpected consequences: space observations are more easy to plan, since the possibilities are defined long time in advance and all parameters are under control. Similar arguments hold for the availability of data from space missions and to the related data reduction procedures.

5. Summary

Almost the entire wavelength range of the solar electromagnetic spectrum is accessible to solar observers and also particles originating from the Sun can be detected over a wide energy range. Ground observations are not competing with space observation. In the contrary, joint observations from space and from the ground constitute an enormous potential for expanding our understanding of the Sun.

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