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Memorie della

Solar Orbiter

The need to go close to the Sun

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Abstract. The key objective of the Solar Orbiter, a mission of the European Space Agency 'Cosmic Vision' Program, is to fully understand how the Sun creates and controls the heliosphere. The issues addressed by the Solar Orbiter concern the solar dynamo, the origin of the solar wind, of the coronal mass ejections which drive the heliospheric variability, of the energetic particle radiation which fills the heliosphere. In order to pursue these investigations a unique mission profile is proposed. The spacecraft will approach the Sun to within 0.28 AU and reach an orbit inclination relative to the solar equator exceeding 25 degrees. The proximity to the Sun will also have the advantage that the spacecraft will fly in near synchronization with the Sun's rotation. The Solar Orbiter launch is foreseen in January 2017.

Key words. space missions – heliophysics – solar physics

1. Introduction

One of the major scientific achievements of the space era is the discovery that we live in the extended atmosphere of the Sun. Five decades of space observations have allowed the access to the full electromagnetic spectrum emitted by our nearby star, from low frequencies to gamma rays, and the detection of the magnetized plasma, crossed by waves and particles, filling the interplanetary space in the Solar System. The region of space influenced by the expansion of the solar corona and perturbed by the variable solar activity is known as the heliosphere. How this region is formed and controlled by the Sun is thus a fundamental question not only from the astrophysical point of view but also in view of comprehending the protected environment where life can indeed originate and evolve, thanks to the magnetic shield that the Sun creates around the Solar System. Solar Orbiter has been conceived as a mission aimed at fully understanding how the Sun creates and controls the heliosphere.

Our present knowledge of the solar corona, the solar wind and the three-dimensional heliosphere is based on the results from a series of successful space missions. The Sun and its atmosphere have been almost continuously investigated by large multi-instrument space observatories, such as the Apollo Telescope Mount on Skylab (NASA, 1972-1973), the first manned observatory in space, the Solar Maximum Mission (NASA, 1980-1989), devoted to studying the active Sun, and the

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Solar and Heliospheric Observatory, SOHO (ESA-NASA, launched in 1995 and still operative) designed to examine the quiet Sun. Such cornerstones have been complemented by a number of space missions (such as Yohkoh, TRACE, RHESSI, Hinode, STEREO, SDO) focused on more specific scientific objectives. The interplanetary space has been explored by space missions, such as Helios 1 and 2 (ESA), in the seventies, reaching close to the Sun in the ecliptic plane (0.3 AU) and Ulysses (ESA), in the nineties, the first spacecraft to set out on a journey through the polar regions of the heliosphere. The strategy of coordinated solar and heliospheric space research on a global scale is now continuing with the aim at the exploration of the region where the solar wind and the heliospheric structures are formed and, at the same time, at linking the wind structures observed in the heliosphere back to their sources at the Sun.

In order to address the central question, concerning how the Sun creates and controls the heliosphere, we need to understand: how the solar dynamo works and drives connections between the Sun and the heliosphere, how and where the solar wind plasma originates in the solar atmosphere, how solar transients drive the heliospheric variability, how the energetic particle radiation is accelerated and fills the heliosphere. Answering these questions requires *in situ* measurements of the solar plasma, fields, waves and particles close enough to the Sun, so that their properties are little modified by transport and propagation processes. As a second step, relating *in situ* measurements back to their sources on the Sun necessitates simultaneous high-resolution imaging and spectroscopy of the Sun, performed from a platform in and out of the ecliptic. These are the major drivers of the Solar Orbiter mission, which will approach the Sun to within 0.28 AU and reach an orbit inclination relative to the solar equator exceeding 25 degrees. The proximity to the Sun will also have the significant advantage that the spacecraft will fly in near synchronization with the Sun's rotation. In such conditions the solar atmosphere and the heliosphere are almost frozen relative to the observer, thus allowing to disentangle their intrinsic evolution from effects due to the solar rotation. The needed combination of *in situ* and remote sensing instrumentation, together with a unique mission profile, distinguishes Solar Orbiter from all previous missions, and enables breakthrough science which can be achieved in no other way.

2. The Solar Orbiter science

The Solar Orbiter mission addresses the central question of heliophysics, that is, how our nearby star generates and perturbs the heliosphere. Below the surface of the Sun, the solar dynamo creates magnetic fields which emerge in the solar atmosphere because of their own buoyancy. They form huge arcades of coronal loops containing enormous amounts of stored energy which can be released in violent explosions and huge eruptions of hot magnetized plasma. These sudden and transient ejections perturb the supersonic solar wind, driven by dynamic and magnetic processes at the Sun's surface. The plasma of the Sun's atmosphere is indeed continuously expanding to surround the Solar System's planets and the space far beyond. The erupted giant plasma bubbles occasionally impact the Earth and its magnetic shield, which is steadily compressed by the impinging solar wind, with transient disruptive effects on space and terrestrial systems and the living ambient itself (Figure 1). These perturbations are not only limited to the Earth environment but involve the whole heliosphere and planets, out to the heliopause, which delimits the boundary with the interstellar space, far beyond Pluto's orbit.

2.1. Solar dynamo

The solar atmosphere is controlled by the magnetic field of the Sun which provides the energy needed to heat the corona and power the most energetic phenomena occurring in the corona and influencing the Solar System. The solar magnetism is variable with a period of 22 years. The dynamo generating the global magnetic field is believed to be seated in the shear layer at the base of the convective zone, which has been revealed via helioseismology.

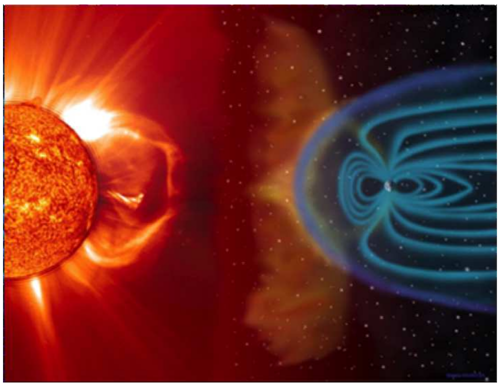

Fig. 1. Artistic view of the interaction of the solar wind and coronal mass ejections with the Earth's magnetosphere.

The magnetic flux associated with decaying active regions is transported to the poles and then down to the shear layer to be reprocessed for the next 11 year activity cycle. This scenario provides a natural explanation of the sunspot cycle, but fails in predicting the future cycles with sufficient accuracy and anomalous quiescent periods that can unexpectedly occur, such has the long quiescent period lasting from 1645 to 1715, named the Maunder minimum, when almost no sunspots were detected. More recently, the onset of the present solar cycle (cycle number 24) has undergone a long unforeseen delay. The global dynamo may also fail to explain the ubiquitous, small-scale internetwork field.

A key objective of the Solar Orbiter mission is to identify the flows involved in the transport of magnetic flux on the solar surface at all latitudes and sub-photospheric depths. The solar poles and their sub-surface regions, although crucial to understand the solar dynamo since approximately each 11 years they are the sites of the magnetic polarity reversal, are not accessible with remote sensing from the ecliptic plane. Hence, they can be observed only with telescopes operating on a space platform outside of the ecliptic plane.

2.2. Solar wind

The mechanical energy of the convective photospheric motions, which is converted into magnetic and/or wave energy, heats the corona and, as a consequence, drives the solar wind. The 11 years activity cycle, related to the 22 years magnetic cycle, modulates the continuous coronal expansion. A fast wind (700-800 km/s, comparatively steady) emerges from open magnetic field regions, known as coronal holes, which are well developed and located at the poles during solar minimum. The processes of energy deposition and acceleration of the fast wind act predominantly in the outer corona and they are very likely related to wave-particle interactions. This interpretation, put forward in the last decade on the basis of the UVCS-SOHO observations, needs to be fully confirmed. A more variable slow wind (300-400 km/s), dominant during the activity maximum and characterized by a different mass flux and composition than the fast wind, flows in the ecliptic plane during most of the solar cycle, thus becoming particularly important to Earth's space environment. The sources and escape mechanisms of the slow wind are still unknown. On the one hand, the slow wind composition is consistent with that of the coronal plasma confined in the magnetic loops. On the other hand, close to the boundaries of coronal holes the flux tubes formed by the open field lines, locally characterized by cross sections highly divergent with height, are channeling plasma flowing more slowly than in the coronal hole cores. Fast and slow wind carry embedded turbulent fluctuations with different characteristics, which may play a crucial role in the acceleration of the solar wind while propagating from the corona to the heliosphere.

Solar Orbiter will measure *in situ* the solar wind plasma speed, composition and magnetic field close to the Sun, where the propagation has not yet substantially modified the physical parameters of the wind structures. At the same time, Solar Orbiter will perform remote sensing observations of the wind source regions in the solar atmosphere. During perihelion segments of the orbit, when the spacecraft is in quasi co-rotation with the Sun, the magnetic connectivity of the heliospheric plasma to its source region will be easily traced. Simultaneously the high resolution imaging and spectroscopy of the source at the base of the solar atmosphere will allow the identification of the phenomena, such as jets, small explosive events, etc., believed to mark reconnection driven plasma outflows in predominantly closed magnetic field regions.

Imaging and spectroscopy of the outer corona during perihelion, when its evolution is not affected by solar rotation, will furthermore allow one to ascertain whether and how the magnetic topology of the open field lines emerging from coronal holes, and its evolution, affects the solar wind speed. These combined observations will determine the relative importance throughout the solar cycle of the slow wind emerging from open versus closed magnetic field regions of the solar atmosphere.

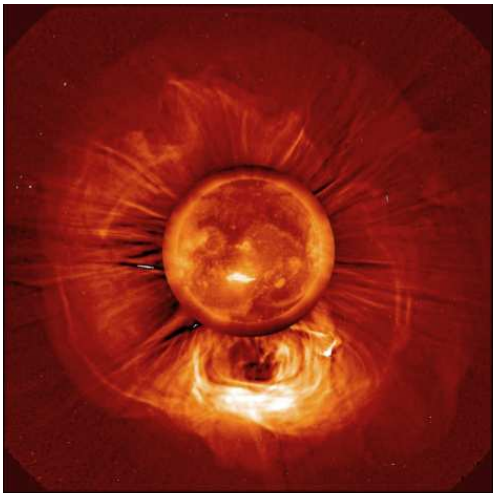

Fig. 2. Example of halo coronal mass ejection, directed toward the Earth and thus impacting the Earth's magnetosphere.

2.3. Solar activity and heliospheric variability

The active Sun exhibits many forms of transient phenomena which affect the structure and dynamics of the outflowing solar wind, and thus in turn of the heliosphere, the most significant and energetic ones being flares and coronal mass ejections (Figure 2), which often occur almost simultaneously. During such phenomena, the Sun emits high frequency radiation up to gamma rays, the most energetic photons in the electromagnetic spectrum, and accelerates high energy particles (protons up 10 GeV), thus acting as the most powerful accelerator of the Solar System.

Explosive and eruptive solar phenomena are driven by a sudden release of magnetic energy stored in highly non-potential field regions. Very energetic solar particles penetrate the geomagnetic field especially at the poles and have consequences on human space activities. In addition, the impact of coronal mass ejections on the Earth' magnetosphere and upper atmosphere has significant consequences for society, human activities and animal behavior. Understanding these impacts, with the ultimate goal of predicting them, has received much attention in the SOHO era, when a large solar observatory is uninterruptedly monitoring the solar corona from the Lagrangian point L1, with highly sensitive instrumentation, thus in fact opening a new applied science known under the name of *space weather*. It is important to stress the fact that, although in a variable way, the solar activity effectively shields the Solar System from the interstellar wind and galactic particle radiation. The activity level modulates, according to the 11 years cycle, the flux of galactic cosmic rays accessing the heliosphere. In this scenario, it is essential to understand: how do coronal mass ejections evolve through the corona and inner heliosphere and perturb the solar wind, how these phenomena contribute to the solar magnetic flux and helicity balance, how and where shocks form in the corona, and how flares and coronal mass ejections accelerate the energetic particle radiation.

Coronal mass ejections appear to originate in highly-sheared magnetic field regions on the Sun. Eruptions develop in the low corona within a few minutes, while the associated shocks cross the solar disk within one hour. Their propagation speed can reach up to 3000 km/s and they carry kinetic, thermal and magnetic energy, up to 10^{32} ergs. Their onset is related to a disruption of the magnetic field balance in the solar atmosphere due to several possible causes, such as, for instance, upper pressure of strongly sheared fields (slowly increasing because of photospheric motions and flows associated with differential rotation), rapid removal of the magnetic tension of the overlying fields, magnetic breakout when tension is removed by reconnection of overlying/neighbouring fields.

Magnetic flux is transported outward from the Sun both by the solar wind, in the form of open flux mostly coming from coronal holes, and by coronal mass ejections which drag closed flux into the heliosphere. The total amount of magnetic flux in the Solar System changes over the solar cycle. In the recent solar minimum this flux has decreased unexpectedly to unprecedented values since this quantity became measurable during the space era (Figure 3). The relative contribution of the solar wind and coronal mass ejections to the magnetic flux budget is an unresolved question, as is the process by which the closed flux added by the coronal mass ejection is removed to avoid its unsustainable buildup in the heliosphere. The plasma injected by the Sun into the heliosphere carries also magnetic helicity away from the Sun. This is a fundamental property of magnetic fields in natural plasmas and is injected in corona when the field, created by the sub-photospheric dynamo, emerges via the twisting and braiding of the magnetic flux. The injected helicity is conserved and tends to accumulate at large-scales. It is natural to assume that a critical helicity threshold may be involved in triggering coronal mass ejections. How solar eruptions depend on the amount of energy and helicity injected in the corona, and on critical helicity thresholds,is still unknown.

The rapid expulsion of mass during coronal mass ejections can drive shocks in the corona and in the heliosphere, when the driver moves at super-Alfvénic speed. Shock waves can accelerate particles by repeatedly imparting many small amount of energy at each step via Fermi or stochastic acceleration. This mechanism can also occur in turbulent regions where magnetic fields reconnect. Alternatively particles can be accelerated to almost relativistic energies when reconnection of magnetic fields creates a strong electric field which can accelerate particles in a single step.

The understanding of the major issues, such as the sudden energy releases occurring in corona associated with huge eruptions of coronal material, the amount of magnetic helicity and magnetic flux carried into the heliosphere by the eruptive material and the solar wind, and the mechanisms accelerating particles are addressed with the Solar Orbiter instrumentation by combining *in situ* measurements of the ejected material close to the Sun with the high resolution spectroscopic and imaging observation of the source regions. As in the solar wind studies, major advancements in the understanding are expected when the spacecraft is in quasi co-rotation with the Sun. It is thus possible to monitor the same coronal region in space for an extended interval of time, in order to track for sufficient time the changes in magnetic configuration prior to the disruption leading to the transient and during the propagation of the eruptive material, and to monitor the reconfiguration of the corona after its passage. In addition, in absence of solar rotation relative to the spacecraft, the same heliospheric region will be probed throughout the passage of a mass ejection.

3. Mission Design

The above brief discussion on the unanswered questions of heliophysics clearly shows the need of a novel unique mission, designed to explore the heliosphere very close to the Sun, to co-rotate with Sun in order to cancel or minimize the effects of solar rotation, to explore by remote-sensing and helioseismologic techniques the poles of the Sun and their subsurface regions. Thus a mission profile for Solar Orbiter has been developed that will, for the first time, make it possible to study the Sun with a full suite of *in situ* and remote sensing instruments from inside 0.28 AU, provide imaging and spectral observations of the polar regions of the Sun from out of the ecliptic, and take advantage of intervals around perihelion of near synchronization of the spacecraft with

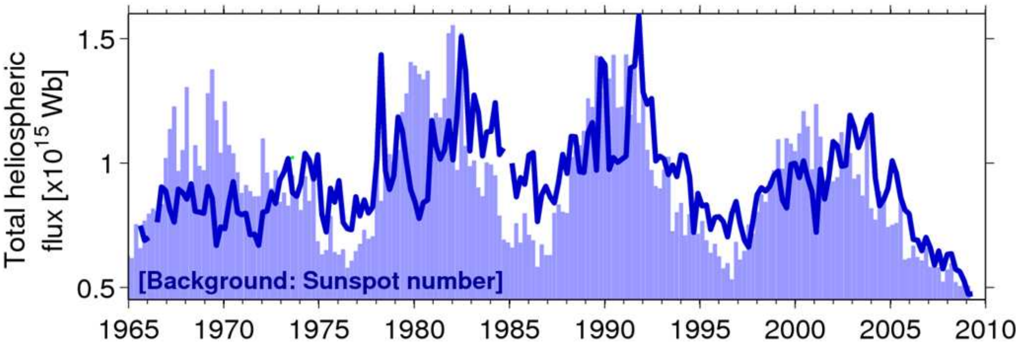

Fig. 3. Magnetic flux measured in the space era in the heliosphere, showing the dramatic decrease observed during the recent prolonged solar minimum (courtesy of M.Owens, Solar Orbiter Assessment Study Report, 2009).

the Sun's rotation to freeze the corona at the solar limb and acquire the capability of tracing heliospheric structures back to their sources.

The mission is planned to start on January 2017 with a launch placing the spacecraft on a ballistic trajectory. A series of gravity assist maneuvers at Earth and Venus will place the spacecraft in an operational orbit with an orbital period of 150 days, a perihelion of 0.28 AU and an initial solar inclination of 7.7 degrees. Further Venus gravity assist manoeuvres will increase the inclination above 25 degrees at the end of the nominal mission, lasting 7.5 years, to reach a maximum of 34 degrees at the end of the extended mission.

4. Italian contribution to the scientific payload

One of the strengths of Solar Orbiter is the synergy between in situ and remote sensing observations ensured by a coordinated suite of 10 instruments. The in situ instruments include: the Solar Wind Analyser, the Energetic Particle Detector, the Magnetometer, the Radio and Plasma Waves detector. The remote sensing instruments include: the Polarimetric and Helioseismic Imager, the Extreme Ultraviolet Imager, the Spectral Imaging of the Coronal Environment EUV Spectrograph, the Spectrometer/Telescope for Imaging X-rays, the Multi Element Telescope for Imaging and Spectroscopy, the Heliospheric Imager. The scientific payload, provided by ESA member states and NASA, has been selected in 2009. The Italian Space Agency (ASI) is engaged in the development of two crucial instruments: METIS, the Multi Element Telescope for Imaging and Spectroscopy (PI, Ester Antonucci) and SWA, the Solar Wind Analyser (Co-PI, Roberto Bruno).

The expertise acquired in contributing to the development and operations of the Ultraviolet Coronagraph Spectrometer (joint ASI-NASA collaboration) for SOHO, has allowed the scientific team, coordinated by the Astronomical Observatory of Turin (INAF), jointly with the Italian industry (Thales Alenia Space, Turin, and Selex Galileo, Florence) to design for the Solar Orbiter METIS, a totally novel coronagraph with both imaging and spectral capabilities.

The involvement over the years in several successful heliospheric space missions has allowed the team coordinated by the Istituto di Fisica dello Spazio Interplanetario -INAF to participate with an important contribution (the instrument data processing unit) in the SWA experiment for the Solar Orbiter. The synergy of METIS with the SWA instrument is quite evident, since SWA analyses the plasma carried by the solar wind and perturbed by the coronal mass ejections which undergo their acceleration and early propagation in the outer corona which is observed by METIS.

4.1. METIS scientific objectives

METIS will investigate the outer solar corona, which is the region connecting the Sun to the heliosphere and where the processes generating and driving the heliosphere occur. The key objectives to be pursued with the METIS coronagraph is to answer the following questions: how energy is deposited in coronal holes to generate the fast wind, what are the sources of the slow wind, which is the role of the helium component in the corona and in the solar wind, and how the global corona evolves and solar transient originate. In more detail the METIS observations are designed to:

- clarify the nature of the mechanism of energy deposition in the solar wind by observing its effects on the protons and He ions, which, depending on their different charge to mass ratio, are differently affected when interacting with the high-frequency part of the spectrum of outward propagating Alfvén waves (ion-cyclotron resonance);
- discover the nature of coronal fluctuations and their role in transferring energy from the inner atmosphere to the regions where the solar wind is accelerated (observations of the corona during quasi co-rotation allows us to distinguish the fluctuations arising from the rotation of magnetic flux tubes and those induced by wave propagation and/or inhomogeneities carried by the wind);
- assess the role of the magnetic topology in controlling the solar wind speed and properties, in order to identify the slow wind sources, by measuring the helium abundance which provides a decisive test in this respect;
- identify the solar energetic particle accelerated by the shocks driven by mass ejections in the corona on the basis of their spectroscopic signatures;
- identify the mechanism driving the eruption of coronal mass ejections and understanding the evolution of the global corona, as the result of the opportunity to observe, during co-rotation, the evolution of the corona over times much longer than the 2-3 days passage of the coronal structures at the limb, and in addition to observe the corona from out of the ecliptic, thus viewing the longitudinal extend of the large scale coronal structures.

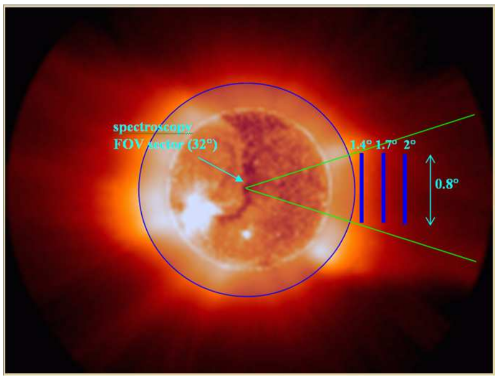

Fig. 4. Field of view at minimum perihelion of the METIS coronal images and of the sector where imaging-spectroscopy of the solar corona is performed.

These major open issues in the understanding of the solar atmosphere can be effectively addressed by performing a complete characterization, in terms of structure, dynamics and abundance of the three most important plasma components of the solar atmosphere: electrons, protons and helium. In order to achieve this information, images of the full corona in polarized visible light and in the emission of hydrogen and helium (in the ultraviolet and extreme ultraviolet domain, respectively) will be obtained, except in a sector 32 degrees wide where H and He spectra will be detected. At present only visible light coronal images and UV coronal spectra are available for coronal studies.

Since the Solar Orbiter mission will probably partially overlap the NASA Solar Probe mission - aimed to carry in situ instrumentation very close to the Sun in the ecliptic plane -, METIS will also image and spectroscopically observe the plasma crossed by the Solar Probe in its journey around the Sun. Thus for the first time plasma of the extended solar atmosphere, and in general an astrophysical plasma, will be simultaneously probed *in situ* and observed by a remote sensing instrument.

4.2. METIS instrument concept

METIS combines and extends the imaging and spectroscopic capabilities of the previous SOHO and STEREO coronagraphs. Simultaneous broad-band polarized imaging of the visible K-corona and monochromatic imaging of the HI Ly alpha, 121.6 nm, as well as imaging of He II Lyman alpha, 30.4 nm, will be obtained with spatial resolution down to about 2000 km in the altitude range from 1.5 to 3 solar radii, at minimum perihelion. METIS will image the full corona, except in a sector 32 degrees wide where spectra in the regions of the HI and He II Ly alpha lines will be detected (Figure 4). The coronagraph is based on a novel externally occulted design. The unique capabilities of METIS of imaging the solar corona in three different wavelength bands by means of a single telescope is achieved by multilayer coatings of the mirrors, optimized to detect He 30,4 nm. The capability of acquiring simultaneous spectra at three different heights in corona is ensured by inserting a small grating and a multi-slit along the optical path. The multi-wavelength coronagraph concept has been successfully tested by launching in September 2009 a METIS prototype, SCORE, in a suborbital flight of the HERSCHEL experiment of the NASA LWS technological program. The experiment has provided the first He image of the solar corona.

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References

Antonucci, E. 2005, The scientific possibilities for coronagraphy from the Solar Orbiter, Advances in Space Research, 36, 8, 1367–1374

Solar Orbiter A High-Resolution Mission to the Sun and Inner Heliosphere, Assessment Study Report, ESA/SCI (2000) 6, July 2000

Solar Orbiter - Exploring the Sun-heliosphere connection, Assessment Study Report, ESA/SRE (2009) 5, December 2009