EUROPEAN PLANS FOR THE SOLAR STEREO MISSION
- BRIEF SUMMARY OF THE EUROPEAN STEREO STEERING TEAM (ESST) -

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ABSTRACT

The concept of a solar Stereo mission has received strong interest in the solar and heliospheric physics community due to its enormous and wide range scientific potential. A solar Stereo mission is being considered as one of the prime candidates for a future scientific space mission in solar and heliospheric physics within the space science programmes of ESA and NASA. NASA has recently implemented the STEREO mission in its Solar Terrestrial Probe Line and a science definition team has been set up for its development. In Europe, a Stereo steering team has been formed to help explore the full scientific potential of a Stereo mission in collaboration with NASA’s science definition team, to study its technical and financial feasibility within the frame of ESA’s space science programme and to investigate necessary technology developments.

This paper presents a brief overview on the prime scientific objectives of a Stereo mission that were identified within the European solar and heliospheric physics community, possible Stereo mission scenarios including in- and out-of ecliptic type missions, either as ESA, ESA/NASA or joint international missions and the scientific instruments under discussion. The paper finally points out what appears to be the most attractive Stereo mission scenario and addresses the importance of international collaborations.

1. INTRODUCTION

The Sun may be considered as a rather ordinary star within our galaxy. However, it plays a dominant role for human beings because it sustains life on our home planet. Occasionally violent solar eruptions affect strongly our geospace environment and the influence of the Sun can become directly obvious to us in form of telecommunication disruptions or power outages. As space based technologies become more and more important for our modern life, e.g., through increasing use of Global Positioning Systems (GPSs), it also becomes more and more important to better understand the physics of the Sun and the heliosphere and the physics of the Sun-Earth connections, often referred to as space weather in a more popular terminology. Only recently, in January 1997, scientists found direct evidence from observations of the ESA/NASA SOHO (Solar and Heliospheric Observatory) spacecraft that a solar eruption caused a few days later a strong disturbance of the Earth’s space environment which in consequence likely led to the loss of a communication satellite (for more information see http://www.istp.gsfc.nasa.gov/istp/cloud_jan97).

The Sun is the only star which we can study in great detail. It is important to emphasize that it is a magnetic star since the origin and role of magnetic fields, their evolution and dissipation in the Universe, are key questions in space physics and astrophysics. The variability of the Sun’s magnetic field for example modulates the entire solar system including the near Earth space environment. Long-period variations can be related to climatic changes on the Earth while on shorter timescales magnetic field changes are responsible for dramatic responses in the Earth’s magnetosphere. Solar flares and coronal mass ejections (CMEs) are spectacular manifestations of the Sun’s magnetic activity. Recent space-based observations from SOHO or the Japanese Yohkoh satellite have yielded breathtaking observations of the ever changing Sun and corona. Even at times of solar activity minimum the Sun and heliosphere are highly structured and time-varying objects.

SOHO currently studies the physics of the Sun from


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its deep interior to the outer atmosphere up to its consequences at Earth's orbit with unprecedented resolution. With SOHO we have gained a totally new view of the Sun's variability and many scientific breakthroughs in various areas of solar and heliospheric physics have already been made or are still to come during the next years. However, it is obvious that these observations have also brought up new scientific questions and have demonstrated the current observational limitations. Solar observations in high spatial and temporal resolution (see, e.g., Rust, 1996; Maltby and Battrick, 1993) and the removal of foreshortening effects in line of sight observations (Liewer et al., 1998; Cartridge, 1997; Grigoryev, 1993) are prime targets for future solar explorations (Bothmer and Marsch, 1997).

All current detailed observations of the Sun have been taken so far from one vantage point only, namely from Earth's orbit. However, this perspective does not allow a detailed investigation of those solar source regions that are associated with eruptions that directly propagate towards the Earth, i.e. the most effective ones in terms of space weather. For a better understanding of the physical processes, simultaneous space-based solar and heliospheric observations and in-situ measurements from more than one perspective and away from the Sun-Earth line are necessary (Brueckner, 1995; Harris, 1995).

The importance of simultaneous observations of the Sun and the heliosphere through multiple spacecraft from new vantage points has been recognized from the very beginning of the space age and consequently the importance of multipoint solar/heliospheric missions has been emphasized previously (see, e.g., Huber, 1997; Calder, 1995; Delache et al., 1984). However, it often takes a long time to make the necessary technical developments to allow sophisticated space missions scientists have dreamed of to become scientifically, technically and financially feasible. It seems now being timely to start developing a solar Stereo mission ready for launch in the first decade of the new millenium.

2. SCIENTIFIC OBJECTIVES

Key questions that have dominated research in solar physics for decades concern the structure of the solar interior, the heating of the solar corona and the acceleration of the solar wind. Major breakthroughs in these research areas can be expected from SOHO or TRACE (Transition Region And Coronal Explorer) during the next years.

The understanding of the solar magnetic field in 3 dimensions, its origin, variability and evolution remain key questions. These questions cover many different physical aspects ranging from the interior of the Sun to the physics of the Sun's atmosphere into the heliosphere and the effects at Earth. Solar flares and CMEs are the most energetic phenomena in the solar atmosphere. Many previous missions, e.g., the SMM (Solar Maximum Mission) have focussed its scientific objectives on the understanding of flare processes. However, it has now become common knowledge that CMEs, which have been first discovered in the early seventies of this century, play a key role in the variability of the Sun's outer corona and are the solar phenomena that have the strongest effects on our near Earth space environment, namely the strongest geomagnetic storms, telecommunication disruptions and radiation hazards are all caused by CMEs. Research on CMEs can thus provide a great step forward in the understanding of the Sun-Earth connection and in terms of space weather.

The Sun is a 3-D star and CMEs have been identified as a key part of the physics of the Sun. The onset of CMEs, their relationship to active regions, prominences and other solar features, their 3-D structure and their evolution in the heliosphere are today still a mystery. To better understand the global structure and variability of the corona and the physics of CMEs can thus be considered as a major scientific challenge that provides direct benefits for a more reliable performance of many technology systems used on Earth and in space.

The detailed detection of CMEs and measurements of their physical characteristics, such as speed, kinetic energy, total mass or estimates of their internal magnetic field strength and structure requires observations from new vantage points away from the Sun-Earth line, in contrast to current space-based solar observations. Spacecraft suitably located to detect earthward directed CMEs could forecast major disturbances at the Earth about 1.5 to 5 days in advance, depending on the CMEs speeds and the time they need to travel from Sun to Earth. It should be stressed here that the detection of Earth-directed CMEs is a very important aspect of a Stereo mission because it provides a very attractive public outreach and shows that a space mission can have direct benefits for mankind.

Understanding the physics of CMEs has thus been identified as one of the prime topics in solar and heliospheric physics within the European space physics community. Research on CMEs is also closely linked to many other important research topics in solar/heliospheric physics, such as the physics of the solar dynamo, active (and quiet ?) magnetic regions, solar prominences, magnetic flux rope formation, eruption and evolution, the nature of global coronal and heliospheric disturbances, the cause of major energetic particle events that can cause radiation hazards to Astronauts, decreases in cosmic ray intensity (and in the long-term of subsequent effects on Earth's climate ?), for the principle of conservation of magnetic helicity in astrophysical plasmas or the interaction of magnetized space plasmas to name a number of topics amongst many others.

To avoid the line of sight ambiguities in measured solar parameters, for the investigation of the large-scale structure of solar phenomena and to better understand the global behaviour of the Sun and corona it is necessary to have simultaneous measurements from at least two spacecraft. Other research areas such as helioseismology, solar irradiance variability or hard X- and γ-ray observations would also greatly benefit from multipoint observations.

The following list is thought of as a brief overview on the science objectives that will be addressed and of the benefits provided by simultaneous multipoint spacecraft observations of the Sun and the heliosphere based on discussions within the European
Possible Mission Scenarios

Figure 1. Sample Stereo in-ecliptic spacecraft configurations.

Stereo Configuration Including An Out-Of Ecliptic Spacecraft

Figure 2. Sample Stereo spacecraft configuration including an out-of ecliptic spacecraft.
Stereo Steering Team:
- Investigations of active regions and possible onset/source regions of CMEs without line of sight foreshortening and limb occultation.
- Detection and identification of geoeffective CMEs and those which accelerate energetic particles.
- Combined photospheric/coronal studies through correlated disk and limb observations. Combined measurements by imaging and spectroscopy of near-limb features, e.g., diagnostics and doppler measurements in plumes, macropicules, spicules, sprays, surges, etc.
- 3-D structure of solar magnetic features.
- 3-D magnetic reconnection.
- Physics of the corona on global scales.
- Evolution of solar regions over much shorter time-scales than one solar rotation.
- Space plasma interaction in the solar corona and heliosphere.
- Particle acceleration at the Sun and in the heliosphere at large-scale.
- Multidimensional tracking, imaging and sampling of CMEs and prediction of their arrival at Earth.
- Combined remote sensing and in-situ measurements of CMEs.
- Large-scale structure and evolution of CMEs, shocks, energetic particle events and corotating interaction regions (CIRs).
- First real time space weather forecast.
- Improved helioseismology and solar irradiiance studies.

3. STEREO MISSION SCENARIOS

3.1. European Stereo Mission Studies

Stereo Mission scenarios that have been studied in Europe are shown in Figure 1. The left diagram of Figure 1 represents the Lagrange proposal of Schmidt et al. (1996) for ESA’s call for mission ideas for the M3 cornerstone of the Horizon 2000 Plus programme (Battrick, 1995) in 1993. Solar/heliospheric Stereo missions that were studied within ESA in the frame of the Horizon 2000 Plus programme included scenarios with up to 6 spacecraft (see Figure 1 middle and right diagrams) in orbit around the Sun at 1 AU in the ecliptic and an additional scenario of a stereoscopic Solar Corona Probe mission (Racca, 1997; Malthby, 1997). Detailed values of spacecraft and instrument masses or estimated telemetry rates can be found in the papers by Schmidt and Bothmer (1996) and Racca (1997). In these mission studies the Ariane 5 launcher has been considered as baseline.

In the Lagrange scenario one spacecraft is located about 60° away from the Earth to the East at 1 AU in the L5 libration point of the Sun-Earth system and the other one is in orbit in L1. The spacecraft configuration offers correlated solar limb and disk observations and the investigation of solar active regions on much shorter time-scales than one solar rotation. It also allows detection of earthward-directed solar eruptions and their in-situ probing as well as a forecast and investigation of the corotating solar wind stream structure some days before it passes the Earth. Note that one also gets information about the solar wind structure into which earthward-directed CMEs may propagate and that at least partially a view of the hidden side of the Sun as viewed from Earth can be obtained. However, the scenario does not allow an accurate investigation of the 3-D structure and characteristics of CMEs or substantially improved investigations of the global corona.

An improved global view of Sun, corona and heliosphere and reliable determinations of parameters such as direction of propagation and large-scale structure of CMEs, which provide important implications for their possible terrestrial consequences, can be achieved by placing two spacecraft into orbit to the East (spacecraft lagging Earth’s orbit in the sense of planetary motion) and West of the Earth (spacecraft leading Earth’s orbit in the sense of planetary motion). A third spacecraft near Earth, e.g., in L1, provides on disk observations and in-situ monitoring.

Real tomography of the corona requires a larger number of spacecraft around the Sun (Davila, 1993) as shown in the right diagram of Figure 1 for a configuration based on six spacecraft in orbit in the ecliptic at 1 AU all around the Sun.

Since the payload mass decreases rapidly with the number of spacecraft under the assumption that just a single launch vehicle will be foreseen, a multi-spacecraft mission could carry less instrumentation, e.g., no optical telescopes or magnetographs. Thus, a two spacecraft mission has been favoured.

3.2. Scientific Payload

Table 1 provides an overview on the scientific instruments for a solar Stereo mission that have gained prime interest within the European community and which help to fulfill the scientific objectives summarized in section 2. The second column of the Table briefly addresses the main scientific objective of each instrument, the third column of the Table refers to a sample experiment already developed for a space mission. Note that the listed instrumentation is not necessarily complete and that unlikely all the instruments can be placed on a Stereo spacecraft. The discussion whether individual spacecraft should have the same or different scientific payloads depends on the identified key scientific objectives and of course on the mission cost frame and payload mass margins.

3.3. NASA’s STEREO Mission

NASA has implemented the STEREO mission within its Solar Terrestrial Probe Line (STPL) (Burch, 1997). The entire programme comprises five missions with a scheduled launch for the first mission in 2000. The five missions are: Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics mission (TIMED), Solar-B, STEREO (Solar Terrestrial Relations Observatory), Magnetospheric Multi-scale and Global Electrodynamics.

The STEREO Mission defined by NASA’s science definition team is based on two spacecraft that drift
in the ecliptic at 1 AU, one leading, the other one lagging Earth’s orbit, so that the angles between the spacecraft gradually increase with time. A summary on the mission details and scientific objectives can be found in the report of the science definition team (Rust et al., 1997). The main objective of the mission is to study the physics of CMEs and their terrestrial consequences. The scheduled launch is currently planned for 2003/4. NASA has encouraged European participation in this mission at all levels (G. Withbroe, priv. communication). Cooperation between the European Stereo Steering Team and NASA’s science definition team has been officially established.

Figure 2 shows a Stereo-type mission based on 4 spacecraft including one spacecraft out-of the ecliptic in a highly inclined orbit around the Sun. An out-of-ecliptic inner heliospheric spacecraft to study the Sun and heliosphere at high latitudes can provide a real 3-D view. This scenario has been identified as highly scientifically attractive (Bothmer et al., 1997; Rust, 1996; Pizzo, 1994; Delache et al., 1984; Cooper and Burch, 1991), but may only be achieved through multi-space agency collaborations because of the substantial mission development costs. The possibility of an out-of-ecliptic mission in the inner heliosphere will be discussed in more detail in the next section.

4. SOLAR POLAR ORBITER AND SOLAR QUARTET

The idea of imaging the solar polar regions dates back at least to the early phase of the development of the Ulysses mission. An out-of-ecliptic spacecraft in the inner heliosphere was regarded as a highly desired mission in the discussions within the international solar/heliospheric physics community and within the European Solar Stereo Steering Team. One of the problems of such a mission is the technical difficulty to place a spacecraft in a suitable orbit within a moderate time period. A 1 AU circular orbit may be achieved by multiple Venus and Earth gravity assists. However, it takes about 5 years to reach an inclination of about 30° to the ecliptic using this method.

Recently, a study on a Solar Polar Sail Mission has been performed by a US science team under the lead of M. Neugebauer and P.C. Liewer of the Jet Propulsion Laboratory (JPL) at Pasadena, California (Neugebauer et al., 1998). The study was initiated by new technology studies on chemical propulsion and solar sails in the USA and Europe (see, e.g., Vulpetti and Scaglione, 1996). The study team came to the conclusion that a 90° circular orbit around the Sun at 0.5 AU can be achieved within less than 4 years using 200 m long sails on both sides of a small spacecraft that could carry about 30 kg scientific payload. Requirements for the technical feasibility of this mission is based on successful tests of solar sail deployments in space and developments of lightweight spacecraft subsystems and instruments.

Figure 3 shows the orbits of Solar Quartet, a concept that consists of 4 spacecraft which are in orbit around the Sun in the inner heliosphere. The two drifting STEREO spacecraft launched in 2004 would provide the first quasi 3-D observations of Sun and heliosphere and detect earthward-directed solar eruptions from new vantage points away from the Sun-Earth line. Based on the conclusions of the Solar Polar Sail Mission study it is assumed that a Solar Polar Orbiter (Sun-Earth Resonance Orbiter (SERO)) in Figure 3) could explore for the first time the polar regions of the Sun and the inner heliosphere and the structure of the inner heliosphere at all latitudes. The Solar Polar Orbiter (Sun-Earth Resonance Orbiter (SERO)) has an inner heliospheric orbit with 90° inclination to the ecliptic at 0.5 AU and is in 3:1 resonance with Earth’s orbit. A complete orbit around the Sun takes 4 months. At the same time the Sun-Earth Monitor (SEMO) surveys the solar output at Earth’s orbit. The Solar Polar Orbiter could be launched as an ESA F2/3 mission in 2007/8. In case the STEREO mission would still be in operation at that time, Solar Quartet would provide real 3-D solar/heliospheric perspectives.

A Solar Polar Orbiter would offer first observations for a wide range of research areas in space physics. Due to the limited payload mass, the scientific objectives might be limited to large-scale physics primarily.

Prime scientific objectives addressed by the Solar Polar Orbiter are:

- First in-situ exploration of the polar regions of the Sun and inner heliosphere.
- First detailed studies of the solar wind and magnetic field at all latitudes in the inner heliosphere.
- Exploration of the latitudinal extension of the streamer belt and heliospheric current sheet.
- Investigations of the large-scale restructuring of
the solar magnetic field after CMEs.
- Detection of earthward-directed CMEs.
- Exploration of coronal holes and coronal hole boundary changes.
- Exploration of the global corona.
- Studies of the mass outflow over the Sun's poles.
- Studies of the in-situ properties of the solar wind, energetic particles and cosmic rays at all latitudes.
- Exploration of polar microstructure and solar wind acceleration.
- First measurements of solar irradiance variations over the Sun's poles.
- High complementary aspects to other missions (STEREO, Solar Probe).
- Studies of the magnetic flux budget of the Sun at all latitudes.
- Studies of the loss of angular momentum.

6. RECOMMENDATIONS AND OUTLOOK

Based on the assumption that the solar STEREO mission will be launched within NASA's Solar Terrestrial Probe Line in 2004 and that 2007/8 is the earliest possible launch date for an ESA solar mission as F2/3 (flexible mission), the European Stereo Steering Team (ESST) recommends:

- ESA participation in the STEREO mission.
- European participation in the development of experiments for the STEREO mission under ESA endorsement to help maximize its scientific return.
- To study a Solar Polar Orbiter for the inner heliosphere as a prime candidate for ESA's next solar/heliospheric mission.
- To conduct further technology studies to explore in depth the potential of electric and solar sail propulsion techniques.

5. TECHNOLOGY DEVELOPMENTS

New technologies to be developed for a Stereo and Solar Polar Orbiter mission are:

- Optimized data compression.
- Tomographic analysis techniques.
- Lightweight, ultra-low-scatter optics.
- Image reconstruction techniques.
- Spacecraft and experiment miniaturization.
- S/C propulsion techniques (electric propulsion, solar sails).

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