SOHO – AN OBSERVATORY TO STUDY THE SOLAR INTERIOR AND THE SOLAR ATMOSPHERE

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ABSTRACT

The Solar and Heliospheric Observatory, Soho, is a joint venture of ESA and NASA within the frame of the Solar Terrestrial Science Programme. The main objectives of Soho are: a) the study and understanding of solar coronal phenomena; and b) the study of the solar structure and interior dynamics from its core to the photosphere. The primary goals of the coronal and solar wind studies are to understand the coronal heating mechanism and its expansion into the solar wind. These goal will be achieved both by remote sensing of the solar atmosphere with high resolution spectrometers and telescopes and by "in situ" measurement of the composition and energy of the resulting solar wind and the energetic particles that propagate through it. The structure and interior dynamics will be studied by helioseismological methods and the measurement of solar irradiance variations. The Soho spacecraft will be three-axis stabilized and located in a halo orbit around the L1 Lagragian point (approximately 1% of the distance from the Earth to the Sun). It is currently scheduled for launch in July 1995.

1. INTRODUCTION

The Solar and Heliospheric Observatory, Soho, is a space mission that forms part of the Solar-Terrestrial Science Program (STSP), developed in a collaborative effort by the European Space Agency, ESA, and by the National Aeronautics and Space Administration, NASA, of the USA. The STSP, in turn, forms part of ESA's long term science plan known as "Space Science: Horizon 2000" and of NASA's collaborative International Solar-Terrestrial Program (ISTP) with ESA and with ISAS (Institute of Space and Astronautical Science, Japan).

This chapter presents an overview of the Soho mission in terms of its overall scientific objectives and its complement of instruments. It serves as an introduction to the description of the individual investigations that are described in the following chapters.

2. SCIENTIFIC OBJECTIVES

The Sun is the only star that we can study with more information than that transmitted by the integrated spectral flux of the electromagnetic radiation and its fluctuations. We can observe images of the Sun and use them to study plasma processes occurring in different parts of its atmosphere. For phenomena occurring in the outer atmosphere (outside the photosphere) we are frequently able to determine many aspects of the interactions between various physical processes such as magnetic field changes, heating, material flow, conduction, and radiation. An important aspect of these processes is the expansion of the solar atmosphere in the form of a wind (solar wind) that blows past the Earth and most of the solar system. We can study this solar wind "in situ" by means of spacecraft that are outside of the Earth's magnetosphere.

The apparent surface of the Sun as seen in visible light is called the photosphere. It is this "surface" or layer from which most of the electromagnetic radiation that reaches the Earth is emitted, and is the region that has been best studied from ground observatories. The intensity distribution of the photospheric radiation peaks in the visible part of the electromagnetic spectrum and it is in this spectral region that the Earth's atmosphere is most transparent.

Above the photosphere the solar atmosphere becomes very tenuous and structured. The temperature reaches a minimum value (approximately 4200K) at the top of the photosphere and then increases first slowly through the chromosphere, then very rapidly through the transition region. In the corona or outermost part of the atmosphere the temperature reaches very high levels (more than 10 degrees Kelvin). All the layers above the photosphere are extremely dynamic, and in fact the layered structure as defined above is only an abstraction since the solar atmosphere consists of many magnetic flux tubes in the forms of simple closed loops, twisted loops, and open magnetic structures. Moreover, the whole solar atmosphere is subject to continuous changes that, triggered by photospheric activity, propagate through the different layers.

The layers above the photosphere cannot be studied from ground observatories for two main reasons. One is that they are so tenuous with respect to the photosphere that any emission that they produce at visible wavelengths cannot be seen against the photospheric background.

…Scientific and Technical Aspects of the Instrument (ESA SP-1104, February 1989)

Table 1: Soho investigations and resources alocated

Investigation	Principal Investigator	Measurements	Technique	Mass (kg)	Power (W)	Bit rate kb/s
HELIOSEISMOLOGY						
Global oscillations at low frequencies (GOLF)	A. Gabriel, LPSP, Verrières-le-Buisson, F	Global Sun velocity and magnetic field oscillations Harmonic degree l = 0-4	Na-vapour resonant scattering cell, Doppler shift & circular polarization	31.2	30.0	0.128
Variability of solar irradiance (VIRGO)	C. Fröhlich, PMOD/WRC, Davos, CH	Low degree (l=0-7) irradiance oscillations and solar constant	Global Sun & low resolution (12 pixels) imaging, active cavity radiometers	14.6	16.6	0.1
Michelson Doppler imager (MDI/SOI)	P.H. Scherrer, Stanford Univ., Calif.	Velocity oscillations, high degree modes (up to l = 4500)	Doppler shift with Fourier tachometer, 4 & 1.5 arc sec resolution	43.4	55.0	5 (+160) *
SOLAR ATMOSPHERE REMOTE SENSING						
Solar ultraviolet emitted radiation (SUMER)	K. Wilhelm, MPAE, Lindau, D	Plasma flow characteristics (temperature, density, velocity) chromosphere through corona	Normal incidence spectrometer, 50-160 nm, spectral resolution 2 - 40000, angular res.1.2 - 1.5"	88.0	35.0	10.5
Coronal diagnostic spectrometer (CDS)	B.E. Patchett, RAL, Chilton, UK	Temperatures and density : transition region & corona	Grazing incidence spectrometer 17-50 nm, spectr. res. 5000, angular res. 2"	84.4	45.0	12
Extreme-ultra-violet imaging telescope (EIT)	J.P. Delaboudinière, LPSP, Verrrières-le-Buisson, F	Evolution of chromospheric and coronal structures	Images (1024 x 1024 pixels in 42′x 42′) at lines of He I, Fe IX, Fe XII & Fe XV	17.5	27.5	1
Ultraviolet coronagraph spectrometer (UVCS)	J.L. Kohl, SAO, Cambridge, Mass.	Electron & ion temperatures densities, velocities in corona (1.3 - 10 R_0)	Profiles and/or intensity of several spectral EUV lines between 1.3 & 10 R_0	107.5	35.0	5
White light & spectrometric coronagraph (LASCO)	D.J. Michels, NRL, Washington, DC	Structures evolution, mass, momemtum and energy transport in corona (1.1 - 30 R_0)	1 internal and 2 externally occulted coronagraphs. Spectrometer for 1.1 - 3 R_0	57.4	41.0	4.2
Solar wind anisotropies (SWAN)	J.L. Bertaux, SA Verrières-le-Buisson, F	Solar wind mass flux anisotropies. Temporal variations	Scanning telescopes with hydrogen absorption cell for H Lyman-alpha light	11.6	9.5	0.2
SOLAR WIND "IN SITU"						
Charge, element and isotope analysis (CELIAS)	D. Hovestadt, MPE, Garching, D	Energy distribution & composition (mass, charge & charge state) ions 0.1 - 1000 keV/e	Electrostatic deflection, time-of-flight measurements & solid state detectors	24.5	18.0	1.5
Suprathermal and energetic particle analyser (COSTEP)	H. Kunow, Univ. Kiel, D	Energy distribution & composition, ions 1.2 - 330 MeV/n electrons 0.06 - 25 MeV	Solid state, and plastic and crystal scintillator detector telescopes	18.5	22.0	0.98
Energetic particle analyser (ERNE)	J. Torsti, Univ. Turku, SF					

* MDI will transmit additional 160 kbits/s during the Soho high bit rate transmission mode.

However, some features in the corona can be observed from the Earth during total solar eclipses when the moon, for a few minutes, blocks out the solar disk. Another reason for not being able to study these regions from the ground is that they are at higher temperatures than the photosphere and therefore produce emission lines due to higher levels of ionisation and excitation of the atoms. These lines are generally emitted in the ultra-violet and X-ray regions of the spectrum, to which the Earth's atmosphere is opaque. Thus the outer layers of the solar atmosphere are not generally observable from the ground.

However, the higher temperature of the outer solar atmosphere provides a special opportunity to observe it from space, above the opaque Earth's atmosphere. The higher temperatures and thus shorter wavelengths of emission make the outer atmosphere brighter than the photosphere at many wavelengths. The emission is frequently from specific atomic lines, thus permitting the use of spectral diagnostics to study specific features of the outer atmosphere. Space observations also permit us to study the outer solar atmosphere in visible light with artificial solar eclipses, since they are made from above the scattering due to the Earth's atmosphere.

Previous observations of the Sun from space have been performed by NASA's Orbiting Solar Observatory (OSO) satellites during the 1960's and early 1970's, the Apollo Telescope Mount (ATM) on Skylab during 1972 and 1973, and with the Solar Maximum Mission (SMM) during the 1980's. Many of the observations made by the OSO's and ATM provided the basis for our current understanding of the outer solar atmosphere. The SMM observations further advanced our knowledge, but the experiments were tailored to study solar flares. An important conclusion based on the observations from these previous satellites is that: to understand the processes occurring in the outer solar atmosphere we need simultaneous, high spatial resolution images of the Sun at many wavelengths with a relatively rapid (~1 minute or less) time resolution.

Soho is a solar observatory devoted to furthering our understanding of the outer solar atmosphere and the solar wind. To accomplish this Soho will carry a set of telescopes that will study phenomena that are initiated by processes that commence below the photosphere, and propagate through the photosphere, chromosphere, and the transition region into the corona. These instruments are designed to investigate problems such as how the corona is heated and how it is transformed into the solar wind that blows past the Earth at 400 km/s. To do so they will have spectrometers that will allow the detailed study of the emission and absorption lines produced by the ions present in the different regions of the solar atmosphere. From this information it will be possible to determine densities, temperatures and velocities in the changing structures. These measurements are complemented by the "in situ" study of the composition and energies of the solar wind that results from the coronal structures that have been observed by the telescopes. This is done with the help of particle detectors carried by Soho that sample the solar wind as it passes through it. Soho will thus greatly enhance our knowledge of the solar wind and its source region.

While the solar interior is the region where the kinetic and magnetic energy that drives the outer atmosphere and solar wind is generated, almost no direct information can be obtained about any region below the photosphere. The neutrinos that are generated in the nuclear reactions that take place in the core are the only direct radiation that reaches us from anything that is below the photosphere. But a relatively new technique, helioseismology, has developed in the last two decades that allows us to study the stratification and certain dynamical aspects of the solar interior. It uses the study of the acoustic and gravity waves that propagate through the interior of the Sun and can be observed as oscillatory movements of the photosphere. An analysis of these oscillations allows us to determine the characteristics of the resonant cavities in which they resonate, much in the same way as the Earth's seismic waves are used to determine the structure of the Earth interior.

To study the solar interior Soho will carry a complement of instruments whose aim is to study the oscillations at the solar surface by measuring the velocity oscillations via the Doppler effect and by measuring the oscillating changes in intensity that the pressure and gravity waves produce. The study of such oscillations require both high resolution imaging and long uninterrupted time series of observations. In addition, because it is paramount to understand the structure of the Sun in relation to the oscillation measurements, the total solar irradiance, or solar constant, and its variations will be measured.

The Soho satellite will thus enable us to study: the structure, chemical composition, and dynamics of the solar interior, the structure (density, temperature and velocity fields) and dynamics of the outer solar atmosphere, and the solar wind and its relation to the solar atmosphere.

3. INSTRUMENTATION

The investigations selected for the Soho satellite are listed in Table 1. They can be divided by their area of research into three main groups: helioseismology, solar atmospheric remote sensing, and "in situ" solar wind measurements.

The helioseismology investigations primarily aim at the study of those parts of the solar oscillations spectrum that cannot be obtained from the ground. The required sensitivity for observing the very low modes ($l \lesssim 5$) and the very high modes ($l \gtrsim 200$) is difficult to achieve from the ground because of noise effects introduced by the Earth's diurnal rotation for the low modes, and the transparency and seeing fluctuations of the Earth's atmosphere for the high modes. GOLF and VIRGO aim primarily at the study of the very core of the Sun; for that they have to study oscillations of very low frequencies with very high sensitivity. MDI will observe the whole oscillation spectrum, and will be unique in its study of the upper degree modes that carry information about the composition and dynamics of the outer boundary layer. The three investigations will provide important information about the time varying phenomena in the interior of the Sun.

The Global Oscillations at Low Frequencies (GOLF) investigation will perform uninterrupted velocity oscillation and magnetic field measurements of the full solar disk, spatially unresolved, with extremely high sensitivity (< 1 mm/s and 1 milligauss). To determine the velocity, the Doppler effect is measured by the resonant-scattering technique. A resonant cell filled with sodium vapor in a strong magnetic field enables, by the Zeeman effect, the selective absorption of light in the two wings of the solar D lines. A comparison of the intensity on both sides of the line leads to an extremely sensitive determination of the velocity.

The Variability of Irradiance and Gravity Oscillations (VIRGO) Investigation is an experiment to study the solar irradiance variability and oscillations. The instrumentation of VIRGO comprises two active cavity radiometers observing the total irradiance, and sunphotometers measuring the spectral irradiance at three wave-lengths in the near ultraviolet, the visible and near infrared (335, 500 and 865 nm). In addition, narrow band radiance measurements (at 500 nm) are carried out with 12 resolution elements on the solar disc by a high precision luminosity oscilation imager.

The Michelson Doppler Imager (MDI) will measure velocity oscillations on the surface of the Sun with high angular resolution (4 and 1.5 arc sec). It uses two solid Michelson interferometers as the final elements of a tunable narrow-bandpass filter. Prefiltering is accomplished by a blocking filter and a Lyot filter. The Michelson interferometers are tuned by halfwaveplates. Doppler shifts are determined by measuring intensities at four points along the line profile. The technique yields line-shift estimates with a linear response over a range of +/- 4000 m/s.

The solar atmosphere remote sensing investigations are carried out with a set of telescopes and spectrometers that will produce the data necessary to study the dynamic phenomena that take place in the solar atmosphere at and above the chromosphere. The plasma will be studied by spectroscopic measurements and high resolution images at different levels of the solar atmosphere. Plasma diagnostics obtained with these instruments will provide temperature, density, and velocity measurements of the material in the outer solar atmosphere.

The SUMER, CDS, and EIT experiments are highly complementary in terms of the scientific objectives they can achieve. CDS obtains data on hotter lines, while SUMER obtains somewhat cooler lines, with an overlap between 50 and 80 nm. They both obtain spectra along a spatial line on the Sun, building up a two dimensional image by moving the Sun's image across a slit in a very short time (on the order of seconds). CDS has a broader spectral range at any one time, but cannot obtain line profiles. SUMER, on the other hand, has a high spectral resolution but a limited simultaneous range. Thus, CDS is better suited for density and temperature diagnostics, while SUMER is better suited for velocity measurements. Finally, EIT provides high resolution images of the whole Sun at several temperatures (HeII 30.4 nm ~60,000K, FeIX 17.1 nm ~10^6K, FeXII 19.5 nm ~1.6×10^6K, and FeXV 28.4 nm ~3×10^6K), thus providing the morphological context of the spectral observations.

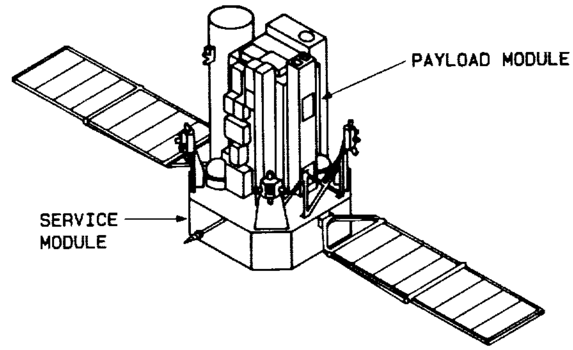

Figure 1 Artist impression of a possible Soho spacecraft configuration

While the CDS, SUMER and EIT primarily observe on the solar disk, the UVCS, LASCO, and SWAN experiments make observations in the solar corona. UVCS observes line profiles in the ultra-violet using Doppler dimming and broadening to determine material velocity and temperature. LASCO uses white light measurements to obtain electron density in the corona and spectral observations of emission lines and Fraunhofer lines to determine the hot coronal temperatures and electron temperature respectively.

The SWAN experiment monitors the large scale properties of the solar wind expansion, and in particular the latitude distribution of the solar wind mass flux from equator to pole, and the time variations of this distribution. It does so with Lyman alpha sky maps of interplanetary emission, obtained with an Hydrogen cell and an apropriate optical scanning system.

The instruments to measure "in situ" the composition of the solar wind and energetic particles will determine the elemental and isotopic abundances, the ionic charge states and velocity distributions of ions originating in the solar atmosphere. The energy ranges covered will allow the study of the processes of ion acceleration and fractionation under the various conditions that cause their acceleration from the "slow" solar wind through solar flares. The CELIAS instruments concentrate on "lower" energy processes while ERNE and COSTEP put their main emphasis on measurements into the suprathermal energy range.

The CELIAS instrument consists of three sensors, all making use of the time-of-flight technique (TOF). The CTOF determines the elemental composition, the charge state distribution, the temperatures and the velocities of the more abundant solar wind ions from helium to iron. The MTOF determines the elemental and isotopic composition of solar wind ions with a mass resolution $M/\Delta M$ better than 100. Finally, the STOF determines mass, charge state and energy of suprathermal and low energy solar energetic particles from hydrogen to the iron group.

The COSTEP and ERNE investigation teams have formed a consortium in which they have defined five sensors that are best suited within the available resources to analyze the composition of the solar suprathermal and energetic particles above the range covered by CELIAS. All the sensors are basically composed of solid state particle detector telescopes. All together they measure, the electron energy spectrum between 60 keV and 5 MeV, the proton fux between 60 keV and 53 MeV, the energy variation of the isotopic composition of ions with energy between 1.4 MeV/n and 53 MeV/n for hydrogen and helium and between 1.6 and 70 MeV/n for Ni. The charge composition determination extends up to 540 MeV/n for elements in the Ni region.

In summary, the coronal remote sensing and the "in situ" experiments on Soho will provide a comprehensive data set to study the solar wind from its source at the Sun through the heliosphere. The solar imagers and spectrographs will allow the study of the morphology, magnetic structure, and heating and particle acceleration processes occurring at the Sun. At the same time it will be possible to make direct measurements of the particle composition and energy spectrum in the solar wind with the particle experiments.

4. SPACECRAFT AND ORBIT

The Soho spacecraft will be three-axis stabilized and pointing to the Sun within an accuracy of 10 arc sec and a pointing stability of 1 arc sec per 15 minutes interval. It will consist of a payload module which accommodates the instruments and a service module carrying the spacecraft subsystems and the solar arrays. The total mass will be about 1350 kg and 750 W power will be provided by the solar panels. The payload will weigh about 650 kg and consume 350 W in orbit. Figure 1 shows an artist's conception of a possible configuration for Soho.

Soho is planned to be launched in March 1995 and will be injected in a halo orbit around the L1 Sun-Earth Lagrangian point, about 1.5×10^6 km sunward from the Earth (Figure 2). The halo orbit will have a period of 180 days and has been chosen because, 1) it provides a smooth Sun-spacecraft velocity change throughout the orbit, appropriate for helioseismology, 2) is permanently outside of the magnetosphere, appropriate for the "in situ" sampling of the solar wind and particles, and 3) allows permanent observation of the Sun, appropriate for all the investigations. The Sun-spacecraft velocity will be measured with an accuracy better than 2 cm/s.

Soho is being designed for a lifetime of two years, but will be equipped with sufficient on board consumables for an extra four years.

5. OPERATION, DATA AND GROUND SYSTEMS

The Soho telemetry will be received by ground stations of NASA's Deep-Space Network (DSN) during three short (1.3 hr) and one long (8 hr) periods per day. Scientific data acquired outside these periods will be stored on magnetic tape onboard the spacecraft and transmitted to ground during the short ground contact periods. The Soho payload will produce a continuous stream of 40 kilobits/s, however the bitrate will be increased by 160 kilobits/s whenever the solar oscillations imaging instrument is operated in its high bit-rate mode. This will happen either daily during the 8-hr periods or during dedicated campaigns when

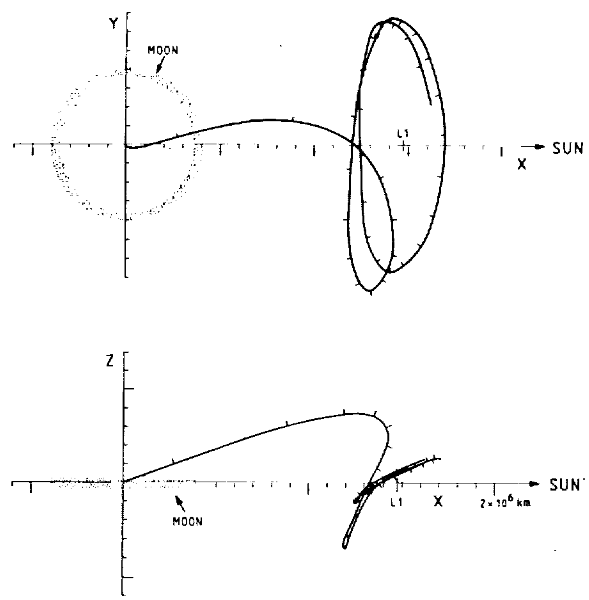

Figure 2 Soho insertion and orbit projection in two orthogonal planes

the satellite will have 24 hour DSN coverage. The campaigns will be organized to provide an approximately 2-month long un- interrupted observation by the solar oscillation imaging instrument.

Figure 3 shows a schematic diagram of the main elements of the Soho ground operations system.

An Experiment Operations Facility (EOF), located at NASA's Goddard Space Flight Center, will be used to coordinate and plan the scientific operations of the payload. Its main task will be to organize in particular the real time operation of the payload and control of the solar remote sensing imaging and spectrometric instruments during the daily 8-hr ground contact interval. ESA also intends to issue an Announcement of Opportunity to invite proposals for a second science operations center in Europe.

Moreover, the large amount of solar oscillations imaging data produced by MDI will be the object of a specialised data facility.

6. COORDINATED RESEARCH

The Soho payload has been conceived as an integrated package that requires coordinated operation and data analysis between the investigations aboard to achieve its scientific aims. The Experiment Operation Facility will be the focal point for these coordinated activities. The EOF will also provide a focus for the cooperation with ground observatories that will make observations and measurements simultaneously with Soho in the visible or radio range of the electromagnetic spectrum. Soho will

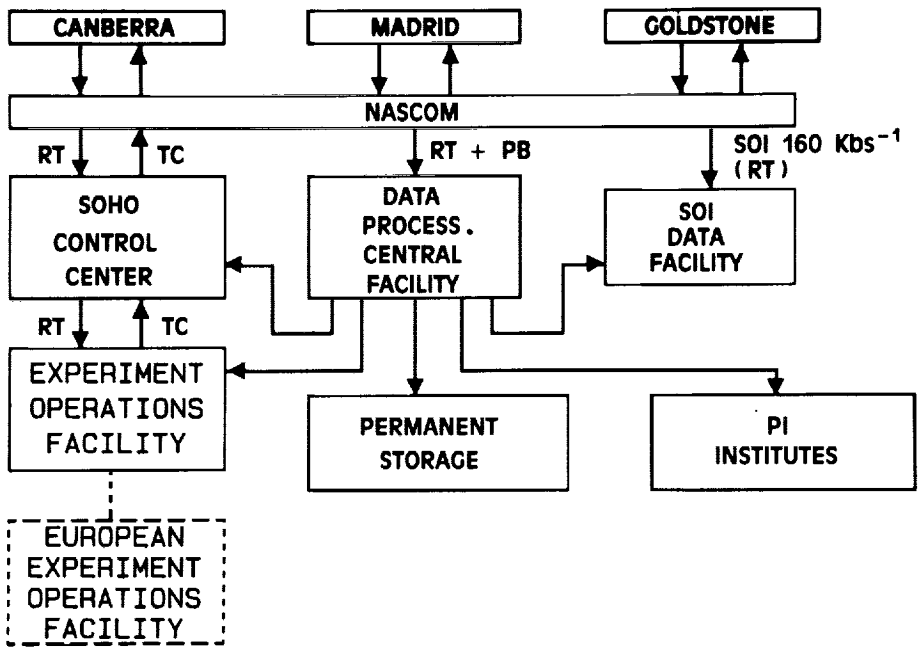

Figure 3 Concept of the Soho ground system

also collaborate with other space missions. For instance WIND and Cluster, when outside the magnetosphere, will provide solar plasma parameters that will complement the coronal and solar wind measurements of Soho. When Cluster is inside the magnetosphere Soho will be a useful monitor for the conditions of the environment external to the magnetosphre.

In the case of Cluster there is another aspect of cooperation that will occur. Considerable mutual insights and cross-fertilisation in the area of plasma physical processes is expected from a coordinated study of the problems investigated individually by each of the two missions. As part of an ESA sponsored workshop, several working groups formulated common scientific objectives and cross-fertilization aspects between Cluster and Soho [ESA, 1985]. Their recommendations point out that most of the processes studied by the one of the STSP components - Soho or Cluster- have counterparts, -or at least analogues, to be studied by the other component. For example, plasma transport into and out of regions of closed magnetic field lines occurs near the Sun and in the Earth's magnetosphere, as well as in many astrophysical contexts. Explosive releases of energy occur both on the Sun (coronal mass ejection), and in the geotail (plasmoid). Magnetic field line merging is a fundamental process that occurs at the Sun and in the magnetosphere and perhaps also in the solar wind. It is particularly associated with extended, thin current sheets, which are observed in the Earth's magnetosphere and are inferred to exist at the Sun. Joint studies by Cluster and Soho will illustrate the roles of the different parameter regimes and the limits of our analogy. This process is particularly important to our attempts to extrapolate and apply knowledge gained in solar-system studies to remote astrophysical objects.

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