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EUROPEAN SPACE AGENCY

SCIENCE PROGRAMME COMMITTEE

Extension of the *SOHO* Mission

Summary

The rationale for extending the *SOHO* mission for an additional 2 years and 9 months is presented.

Required Decision

The SPC is invited to approve the extension of the *SOHO* operations for the period from 1 April 2007 to 31 December 2009 with an increase of XX M€ … in the CaC.

Voting rights and majority required

2/3 of all Member States

Legal basis

SPC Terms of Reference
ESA Convention, Art. XI.5.a.i

1. Introduction

Since its launch on 2 December 1995, *SOHO* has provided an unparalleled breadth and depth of information about the Sun, from its deep core to the outer corona, the solar wind, and the interaction with the interstellar medium. Research using *SOHO* observations has truly revolutionized our understanding of the Sun. The findings have been documented in an impressive and continuously growing number of scientific publications: over 2,500 papers in refereed journals since launch, representing the work of over 2,300 individual scientists. At the same time, *SOHO*'s easily accessible, spectacular data and fundamental science results have captured the imagination of the space science community and the general public alike. *SOHO* images and movies became stock footage for news organizations around the world. As a byproduct of the efforts to provide real-time data to the public, amateurs came to dominate in *SOHO*'s discovery of over 1000 sun-grazing comets.

Here we propose a mission extension of 2 years and 9 months, covering the period from April 2007 through December 2009. This will allow the *SOHO* teams to cover the beginning and rise of the new solar cycle, which according to recent theoretical predictions may start not before 2008. Further, a mission extension will allow overlap with STEREO and Solar-B, both planned for launch in late 2006, and with NASA's Solar Dynamics Observatory (SDO), currently scheduled for launch in late 2008. In the following sections we will highlight some of the unique opportunities afforded by the combination of *SOHO* observations and those from the new missions, and those uniquely enabled by *SOHO*.

Together with *Cluster*, which has been approved for operation through December 2009, *SOHO* will continue to make significant contributions to our understanding of the workings of our solar system, one of the four main goals defined in ESA's "Cosmic Vision 2015-2025". The spacecraft and payload are in good conditions and there are no technical limitations which would prevent *SOHO* from observing for several more years.

In the recent NASA Senior Review of the Sun-Solar-System Connection (S^3C) Mission Operations and Data Analysis Programs *SOHO* was ranked in the excellent category for science merit, and in the compelling category for relevance to S^3C goals. The Panel recommended continued funding through FY10.

SOHO is operated from the *SOHO* Experimenters' Operations Facility at NASA Goddard Space Flight Center (GSFC), and NASA covers the major part of the operating costs. The additional cost to ESA at this stage in the mission represents excellent value-for-money in return for a significant enhancement of the scientific harvest from the *SOHO* mission.

2. Data Accessibility

SOHO enjoys a remarkable "market share" in the worldwide solar physics community: Over 2,500 papers in refereed journals since launch (not counting refereed conference proceedings, which generally duplicate journal articles), representing the work of over 2,300 individual scientists. A searchable *SOHO* publications database[1] is available on the *SOHO* home page. It is not too much of an exaggeration to say that virtually every living solar physicist has had access to *SOHO* data.

[1] http://soho.esac.esa.int /publications/

All of the *SOHO* experiments make their entire data available online on the Web, through the *SOHO* archives and PI sites. A typical PI site, the EIT Web catalog, has served over 1.6 TByte of data since early 2003 – and the EIT database is only 547 GByte as of March 2006. The larger MDI dataset, which includes several levels of computationally expensive, higher-level data products, contains some 20 TByte of data products, and has served over 9 TByte in response to nearly 10,000 online data requests in the last two years. In addition to professional access, amateurs routinely download LASCO images to search for new comets. As a result, nearly half of all comets for which orbital elements have been determined since 1761 were discovered by SOHO, and over two thirds of those by amateurs accessing LASCO data via the Web. An Italian amateur, T. Scarmati, discovered the 1000th SOHO comet on 5 August 2005.

The *SOHO* master archive has been developed at GSFC by the ESA *SOHO* Project Scientist Team. Three copies of this archive have been established in Europe (IAS, France; RAL, UK; Univ. Torino, Italy). *SOHO* data were also among the first data to be fully searchable through the Virtual Solar Observatory (VSO) and the European Grid of Solar Observations (EGSO). Since launch the *SOHO* servers operated by the ESA Project Scientist Team at GSFC have served over 85 TBytes of data and over 275 million web page requests.

3. Recent Scientific Highlights

SOHO provided the first images of structures and flows below the Sun's surface and of activity on the farside of the Sun. It mapped the evolution of zonal, meridional and other large-scale flow patterns below the surface and eliminated uncertainties in the internal structure of the Sun as a possible explanation for the "neutrino problem". It provided evidence for upward transfer of magnetic energy from the surface to the corona through a "magnetic carpet", and revealed an extremely dynamic solar atmosphere where plasma flows play an important role. It identified the source regions and acceleration mechanisms of the fast solar wind, and discovered the large disparity between electron and ion temperatures in coronal holes. It revolutionized our understanding of solar-terrestrial relations and dramatically boosted our space weather forecasting capabilities by providing a nearly continuous stream of images covering the dynamic atmosphere, extended corona, and activity on the farside of the Sun.

A key element in *SOHO* science is the large number of collaborations with numerous ground-based observatories as well as other spacecraft, such as *Ulysses, TRACE*, *RHESSI*, *NEAR*, and *Galileo.* While it is impossible to cover all the findings that have come out of the *SOHO* mission during the 10 years since launch, we will give a brief summary of some recent scientific highlights in the remainder of this section.

Total Solar Irradiance. Interpretation of the total solar irradiance (TSI) record, whether as a steady cycle with no underlying secular change or as showing an increasing trend, has broad social and political impacts as governments make decision on their responses (if any) to global warming. The 10 year long TSI record from the VIRGO radiometers allowed the VIRGO team to develop a new calibration model which enabled them to construct a more reliable total solar irradiance (TSI) composite over the last 26 years. From this composite record it now appears that there is no evidence for a significant long-term, secular trend in the TSI, and that the average amplitudes of the three cycles differ by less than 10%, although each maximum looks quite different.

Rotation of the deep interior. Inversion analysis of the rotational splittings of *p*-modes enables the determination of the core rotation as a function of depth. Results from combining GOLF and

MDI data are consistent with a flat (solid-body) rotation rate of the inner layers down to around 0.2 solar radii.

Solar-cycle variations in the size of the Sun. By analyzing changes of the oscillation frequencies of the *p*-modes, obtained from MDI data, it has been found that the Sun not only becomes smaller at solar maximum but also cooler in the subsurface layers. VIRGO TSI measurements during the same period, however, show a total solar irradiance increasing with increasing solar activity. The solution to the apparent paradox of a smaller and cooler Sun radiating more lies in surface corrugation as a product of the nonuniform distribution of magnetic field – that is, the surface area increases even as the radius shrinks slightly. These helioseismology data also put an upper limit on the possible increase of total solar irradiance (TSI) due to solar activity.

Solar Subsurface Weather. New methods of local helioseismology (time-distance helioseismology, helioseismic holography, and ring-diagram analysis) provide a unique, three-dimensional view of the solar interior. Analysis of MDI data has revealed a fascinating picture of the global-scale, subsurface flows of the Sun, with dramatic changes with the solar cycle. "Solar Subsurface Weather" (SSW) maps reveal large-scale patterns of converging and diverging flows, as well as large jets and circulation patterns. Most active regions show converging flows near the surface but exhibit greater variation at depth. Some of the active regions are marked by inflows at all depths; some possess surface inflows and deeper outflows; and some show strong jets. The primary goal of these studies is the understanding of the life cycle of active regions and relationship between internal dynamics of active regions and their magnetic structure and flaring and CME activity. Of particular interest are measurements of the kinetic vorticity and helicity in the solar interior, and the detection of subsurface shearing flows which can cause shear of magnetic field and trigger instabilities.

Global circulation, solar dynamo, and prediction of the solar cycle. Internal differential rotation and meridional circulation are the most important components of the solar dynamo. Helioseismic observations by MDI have detected changes in the zonal flow pattern in the convection zone of the Sun. The observations revealed the appearance of new branches of torsional oscillations at high latitude in 2002, indicating the onset of the next solar cycle well before the appearance of new cycle sunspot regions. The MDI observations indicate that these new branches originate in the deep convection zone. Further, it was recently discovered in MDI observations that the meridional flow slows down as the solar cycle progresses. This discovery is important for flux-transport dynamo theories which assume that the magnetic polarity reversal in the Sun's polar regions is caused by the transport of magnetic flux by the meridional flow. The deceleration of the meridional flow therefore results in a delay of the next solar cycle. According to new dynamo theory calculations, the next solar cycle will only start in late 2007 or early 2008, six to twelve months later then the current NOAA Space Environment Center prediction, and will be 30–50% stronger than the current cycle.

Farside Activity. In 2000 the MDI team published an astonishing result: the first successful holographic reconstruction of solar farside features from *p*-mode oscillations observed on the visible hemisphere. In the meantime, the astonishing has become routine, and the *SOHO* MDI pages offer daily images of activity on the *entire* surface of the Sun. Another method to monitor solar activity on the farside of the Sun was developed by the SWAN team.

Surprisingly strong magnetic field above a sunspot. Coronal magnetic field strengths of 1750 G at a height of 6 Mm and 960 G at 12 Mm above a pair of large sunspots have been measured by combining microwave observations of third harmonic gyroemission at 15 GHz and 8 GHz with *SOHO* MDI, CDS, and EIT observations. This is the first time that radio brightness temperatures as large as 10^6 K have been observed in a 15 GHz solar radio source above the limb. The field strength measurements yield a magnetic scale height of 10,000 km.

Loop oscillations. The SUMER team has discovered strong Doppler shift oscillations of hot loops above active regions, which later have been identified with slow magnetoacoustic standing waves. This discovery is important for our understanding of the heating of coronal loops, and opened the new research area of "coronal seismology".

CME statistics. The LASCO team has compiled an extensive catalog which summarizes the properties (mass, speed, acceleration, angular width and position, etc.) of the more than 10,000 coronal mass ejections (CMEs) observed since launch. This catalog has been used in numerous studies, including investigations about solar cycle variations of CMEs. The rate of CMEs increases by more than an order of magnitude from 0.5 CMEs per day during solar minimum to over 6 CMEs per day during solar maximum.

The three-dimensional structure of CMEs. Using relatively rare polarized brightness (pB) measurements of the corona by LASCO, researchers were able to present the first three-dimensional reconstructions of CMEs. When combined with the additional views from the coronagraphs on the *STEREO* spacecraft to be launched in 2006, this technique should significantly reduce ambiguities in the reconstruction of interplanetary CME morphology.

CME plasma properties. Analyses of UVCS remote sensing observations of CME plasma properties have provided temperatures, inflow velocities and derived values of resistivity and reconnection rates in CME current sheets, compression ratios and extremely high ion temperatures behind CME shocks, three dimensional flow velocities and magnetic chirality in CMEs, and the thermal energy content of CMEs allowing the first determination of the total energy budget of CMEs.

Origin of the fast solar wind. Recent models based on SUMER and MDI observations support the view of solar wind acceleration in funnel-like flux tubes originating in coronal holes, and isolate the source region for the acceleration of the wind to between 5 and 20 Mm above the solar surface.

HIDEs. Solar wind composition is known to vary modestly as a function of First Ionization Potential, as well as in different solar wind flow types. The CELIAS team, however, has recently identified a new type of event. In these Heavy Ion Depletion Events (HIDEs), He and all the heavier ions are depressed relative to solar wind protons by one to two orders of magnitude.

The interplanetary highway. The discovery of an interplanetary "highway" for solar energetic particles (SEPs) was made possible by exceptionally accurate ERNE measurements of the proton flux anisotropy. During most of the first four hours of the SEP event of 2 May 1998 the proton intensity parallel to the magnetic field was ~1000 times higher than in the perpendicular direction. These observations indicate that the magnetic flux-rope structure of the CME provides a "highway" for transport of solar energetic protons with a parallel mean free path of at least 10 AU.

An interstellar compass. SWAN measurements have revealed that the direction of the interstellar hydrogen flow differs by $4.0^\circ \pm 0.5^\circ$ from that of the interstellar helium; this in turn leads to a determination of the direction and strength of the magnetic field in the local interstellar medium.

4. Why keep *SOHO* going? - Scientific Goals 2007–2010

In the 10 years since launch, research using *SOHO* observations has revolutionized our understanding of the Sun and space weather research. The coming years promise to be similarly exciting and rewarding, when *SOHO* observations will be complemented and enhanced by those from NASA's STEREO and JAXA's Solar-B missions (both scheduled for launch later in 2006). In the following paragraphs we summarize the scientific opportunities afforded by the combination of *SOHO* observations and those from the new missions, and those uniquely enabled by *SOHO*. None of these investigations differs dramatically from the original scientific objectives of *SOHO*: to probe the solar interior and measure solar irradiance accurately; to provide better understanding of the structure, dynamics, and evolution of the outer solar atmosphere; and to study the acceleration and composition of both the solar wind and solar energetic particles. Given the large number of new and enhanced opportunities, we have room to discuss only a few, but they give an excellent indication of the new and continuing opportunities for improved understanding of the Sun-heliosphere system that combining data from *SOHO* and the newer observatories will allow.

Subsurface solar weather. Until the launch of SDO in late 2008, only *SOHO* MDI will be capable of producing the "subsurface solar weather" flow maps and observations of emerging magnetic flux below the photosphere that are at the frontier of our understanding of the magnetic variability that leads to space weather, as well as the solar cycle variations of active region-scale flux emergence.

Acceleration of the solar wind. Among all solar observatories, only *SOHO* UVCS and SUMER are able to monitor ion outflow speeds in the solar corona spectroscopically. Only SUMER can measure ion flow speeds at the coronal base and the initial acceleration, and only UVCS can measure supersonic outflow speeds in coronal holes and streamers. We propose to continue SUMER and UVCS measurements in combination with high resolution *Solar-B* measurements to work toward a quantitative, predictive understanding of the solar wind.

Quadrature observations.. The extended quadrature opportunities with Ulysses in 2006 December – 2007 May (at angular separations of 90º±5º) and 2007 December – 2008 May (90º±10º), will provide "ground-truth" measurements of the interplanetary conditions that *SOHO* will observe to 30 R_{Sun}, while Ulysses is at heliographic latitudes of 60º or more, where the magnetic field should be rooted in the solar polar coronal holes.

CME origin. We have seen the effects of CMEs on the lowest layers of the corona, studied the Doppler motions and heating characteristics of CME ejecta, and detected inflows in the corona, but we still do not know what causes CMEs to erupt, nor how they are accelerated, nor whether the variation in the rate is the same from cycle to cycle. The unique combination of *SOHO*'s remote sensing data with the new measurements of vector magnetic fields, which will be made by *Solar-B* and *SDO*, may provide the key to understand the origins of flares and CMEs.

Precursors to CMEs. Currently, only the *SOHO* mission with its LASCO and EIT instruments provides the full solar hemisphere coverage necessary to allow the detection of precursor events to coronal mass ejections. The *STEREO* spacecraft will significantly expand this program, but will be poorly located for observing many of the precursors of earthward-directed events some two years after launch. Solar EUV imaging will improve dramatically with *SDO*'s launch in late 2008. However, even after this launch, the LASCO coronagraphs will remain unique.

Reconstruction of CME morphology. One of the principal, new areas of investigation that STEREO SECCHI will enable is the tomographic reconstruction of CME morphology. The SECCHI Principal Investigator team has performed reconstructions of simulated CMEs using both two and three viewpoints in the ecliptic plane. The addition of a third viewpoint – *SOHO*'s – can eliminate a critical ambiguity in determining the total amount of material in a CME. The SECCHI PI team "consider[s] the third *SOHO* viewpoint to be critical in obtaining meaningful reconstructions using tomography, and indeed for other reconstruction techniques (forward modeling parameterized solutions, for example) also." (Of course, a viewpoint well out of the ecliptic would provide an even more dramatic improvement over two-spacecraft tomography, but none is on offer before the ESA Solar Orbiter epoch, some ten years hence.) We therefore propose to support STEREO CME tomography efforts by continuing to provide the "third eye" for white-light coronagraphy. Similarly, we propose to continue CDS CME watch campaigns that provide the only current measurements of the speed of plasma erupting from the disk at temperatures up to 2.5 $x10^6$ K.

Multipoint SEP sampling. The combination of instruments on STEREO, ACE, and *SOHO* ERNE, COSTEP and CELIAS provides yet another novel opportunity: measuring the composition and energy spectra of energetic particle events from multiple locations, which should narrow the range of acceleration geometries.

Reconstruction of EUV loop morphology. The STEREO EUV imagers will be used to reconstruct the 3-D morphology of loop systems over the entire disk, but can do so only over a narrow range of spacecraft separations early in the mission: as the spacecraft separate, the area of overlap decreases, and ambiguities brought on by the optically thin nature of the EUV emission increase as multiple features begin to fall along the same line of sight for one spacecraft or the other. The addition of a third viewpoint, that of *SOHO* EIT, will double the length of time over which such reconstructions are possible.

Heliospheric interactions with the interstellar medium. It is not just the plasma and neutral gas in the heliosphere and the interplanetary medium that interact: interplanetary H Lyman α is resonantly scattered by solar wind protons, and full-sky observations can provide us with information on the motion of the heliosphere relative to the local interplanetary medium, and even the direction and magnitude of the magnetic field at the "front" of the heliosphere. Only *SOHO* SWAN can obtain such measurements.

Space Weather Forecasting. There is a recognition that *SOHO*'s space weather capabilities are international resources that should continue uninterruptedly. Even after the launch of *STEREO* later this year, *SOHO* will continue to be the primary source of operational information on the location of origin, speed, and heading of coronal mass ejections from the earth-facing hemisphere of the Sun. In addition, after two years, the angular separation of the STEREO spacecraft will be ~ 90º, and the proportion of earthward-directed events well observed by both spacecraft will begin to decrease.

Solar "forcing" of terrestrial climate. A long-term, accurate, absolutely calibrated record of total solar irradiance (TSI) is essential for answering questions about the degree to which solar forcing affects climate on earth. The 26-year record of TSI will be extended when *SOHO* overlaps with the French *Picard* mission (scheduled for launch in 2008), which will carry an identical suite of radiometers to that in *SOHO* VIRGO.

6. Spacecraft and Instrument Status

All spacecraft equipment is running on the main branch, and the gyroless and intermittent recording software patches perform flawlessly. Solar array degradation so far amounts to only 18.2% (budget was 4% per year), which ensures sufficient power for at least another 6 years. The fuel reserves (118 kg) are also more than comfortable (average use less than 1 kg per year in recent years). Nothing indicates that the spacecraft cannot support an extension through December 2009.

Almost all of the 12 instruments on board are operating at full scientific capability, and can be expected to do so for the next years. On the instrument side there has been only one change since the previous request for extension: One of the two UVCS detectors shows symptoms similar to that of the SUMER A detector. Counts from a few pixel rows appear to be collected in an adjacent pixel row. Like with SUMER, the degradation is along the spatial dimension, which is less of a concern for UVCS. The primary suspect is accumulated radiation damage to the analog-to-digital converters (ADCs) of the crossed delay-line (XDL) detectors. The progressive, expected fall-off in throughput of some of the other instruments is not worrying, and should not prevent SOHO from returning unique science data for many more years.

7. Financial

The rationale for extending the *SOHO* mission until December 2009 has been presented. The SPC is invited to approve this extension.

The cost to ESA for this extension of the orbital operations from April 2007 to December 2009 amounts to XX M€ at XXXX EC.