SOHO, CLUSTER, DOUBLE STAR-THE SUN AND THE EARTH

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ABSTRACT

The 5th anniversary of the launch of Cluster offers an occasion to recall the past history of that mission and how Cluster was eventually included in the ESA Science Program. It is also an occasion to recall how the Chinese Double Star program was initiated and how it complements the Solar Terrestrial Program, Cornerstone of ESA's Horizon 2000 Program, originally made of two missions: SOHO and Cluster. This solar-terrestrial connection has been an essential element to include both missions in ESA's long-term program.

We briefly review the main scientific elements that justify that SOHO and Cluster, together with Double Star, can be considered as two elements of a single Solar Terrestrial Program and we draw some lessons for the future involvement of Europe in the International Living With a Star Program.

1. INTRODUCTION

The ESA Solar Terrestrial Science Program (STSP) was initiated in 1985 after the SOHO and Cluster projects were associated together as what would be the first Cornerstone of the Horizon 2000 program, following a recommendation by the chairman of the Solar System Working Group, Dr M. Huber. The Horizon 200 program was officially accepted by the ESA council in January 1985. While SOHO was designed as a solar physics mission located on a halo orbit at L1, Cluster was a four-satellite mission to study the temporal and spatial variability of the magnetosphere. Gerhard Haerendel, who was advising ESA at that time, insisted that SOHO and Cluster be flown together, in the framework of an International Solar-Terrestrial Physics Programme (ISTP) to be undertaken jointly by ESA, NASA and the Japanese organization, ISAS, because he argued that combining remote-sensing and in-situ observations were going to broaden the science that both missions might achieve. In addition, NASA, together with ESA and ISAS, had organized a Working Group to rationalize the innumerable solar and solar-terrestrial missions then being discussed or planned in these three agencies. The Working Group developed the International Solar-Terrestrial Programme, which naturally included SOHO and Cluster, then in the study stage.

SOHO was the second truly solar physics mission undertaken by ESA after Ulysses, the Out-of-the-Ecliptic mission launched in 1990. Both SOHO and Ulysses have together provided unique contributions to the understanding of solar physics in particular solar magnetism, solar activity, the solar wind and the Corona.

Coupling SOHO and Cluster into a single cornerstone, although justified scientifically, was the result of an opportunistic approach which would secure the existence of each individual mission, preventing each of them to enter into competition against the other. That situation, would have occurred indeed, as the practice at ESA was then to select only one mission at a time.

In the mean time, the perception was growing that the influence of the Sun as the main energy input on the Earth cannot be overlooked when studying the natural and the anthropogenic influences that may affect the Earth climate. This concern is now perceived by the Earth science community as a valid one –that was not always the case-, as can be judged by the organization of a large number of meetings, symposia or colloquia devoted to that subject, such as the two Workshops organized in 2005 by the International Space Science Institute, ISSI: *Solar Dynamics and its Effects on the Heliosphere and Earth***,** *Solar Variability and Planetary Climates***.** In the course of this paper, reference will be made to the relevant presentations given during these two important workshops. The initiation by NASA of the Living With a Star program is another illustration that solar physics and the physics of the Earth climate are connected scientifically and that they should be connected programmatically.

2. SOLAR VARIABILITY: THE ROLE OF THE MAGNETIC FIELD

The Sun is variable on all time scales from a few seconds to billions of years (Fig.1). The origins of these variations are to be found at different depths in the solar interior which can now be probed through the technique of Helioseismology. The variability from very long-term down to a few minutes finds its source in the interior where it is driven by stellar evolution, rotation, convection, and acoustic oscillations. The most spectacular variability is the 11-year activity cycle.

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Within this cycle, the variability down to a few seconds is largely dominated by the solar magnetic field. The Sun is evidently a magnetic star. The variability of the magnetic field manifests itself in these parts of the Sun where the magnetic pressure dominates over the gaseous pressure, i.e. in the photosphere where sunspots are the spectacular signature of concentration of fields of several thousands gauss, and in the corona where the gas pressure becomes very low.

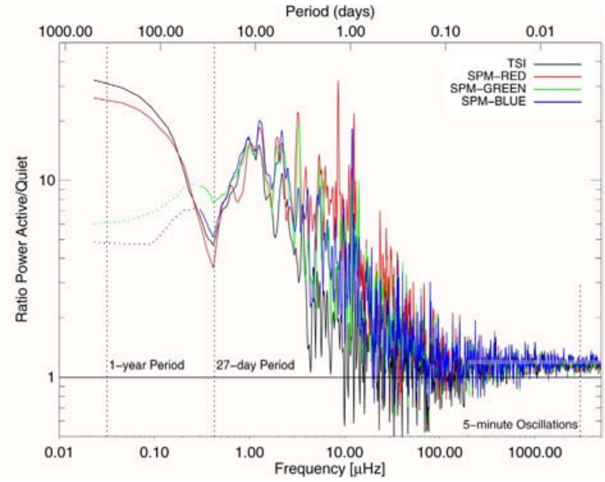

Fig.1. The Sun is variable on all time scales: ratio of the power spectrum of the variability of Total Solar Irradiance and red, blue and green irradiance between the active and the quiet Sun [1]

The number of sunspots present on the disk has been used from observations accurately made since the 19th century as a measure of the level of solar activity; hence, solar activity refers to magnetic activity. The 11-year cycle affects the Heliosphere and the Earth as well as all the planets of the solar system. Solar irradiance, the solar wind, solar energetic particles coming from flares and proton events, Coronal Mass Ejections, all produce their effects at different parts of the Sun-Earth system.

However, the cycle is not regular. Neither the periodicity is precisely 11 years, nor is the intensity of the cycle constant. In fact, there is clear evidence [2] that the heliospheric magnetic flux (the Sun's open flux) has doubled since the beginning of the 20th century. At the same time, the intensity of the cycle is also increasing. Up to now, solar physics and the dynamo theory have been unable to explain such variations. Hence there is a clear need to study the interior of the Sun and the mechanisms that govern the running of the dynamo.

The long-term variability can be established only on the basis of proxies and models (Fig.2). For example, Galactic Cosmic Rays are modulated by the magnetic field. At solar maximum, cosmic rays are deflected by the interplanetary field and are less frequently reaching the Earth, while at solar minimum more of them do penetrate the Earth atmosphere. They do produce radio nuclides, such as ^{14}C and ^{10}Be, whose abundances can be determined with high resolution from tree ring and ice core archives. They consequently provide a tool to reconstruct solar variability over very long time periods reaching back in time ten and hundreds of thousands of years [4].

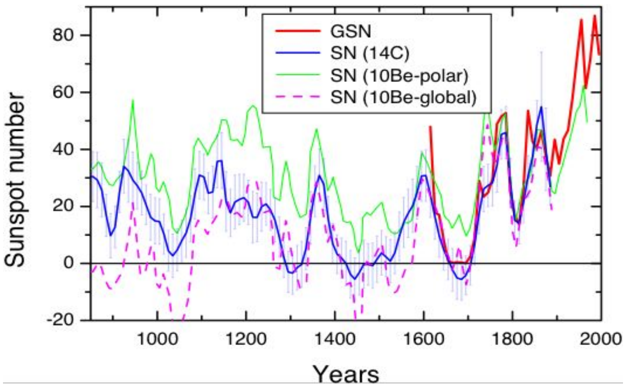

Fig.2. Sunspot numbers reconstructed to 850 years AD [3].

The characteristics of the solar wind itself, its velocity in particular, are connected to the magnetic structures that shape the corona. Ulysses and SOHO have provided ample evidence that the open magnetic structure let the fast solar wind escape the Sun and accelerate to reach some 800km/s. At solar minimum, when the polar coronal fields are shaped by the open configuration of the coronal holes, this fast field fills up the Heliosphere at all latitudes above 30 degrees. At solar maximum, the magnetic field is characterized by a complex network of closed magnetic structures and the solar wind has more difficulties to escape, with a velocity nearly half that of the fast solar wind. Coronal Mass Ejections (CME) are also a manifestation of strongly energetic magnetic reconnection phenomena which inject large quantities of high energy particles into interplanetary medium and make a serious impact on the Heliosphere and on the Earth.

Spectral irradiance in the UV part of the spectrum in particular, which has its sources in chromospheric and coronal structures, is highly variable and modulated by solar activity. Similarly, due to the presence of sunspots and faculae on the disk, the total irradiance of the Sun is also following the modulation of the solar cycle, as shown with great accuracy by satellite measurements made since the mid 1970s, with a most recent and important contribution due to SOHO [1].

3. SOLAR INFLUENCE ON THE EARTH

The Earth magnetosphere, the atmosphere and the climate seem to react to solar forcing. Given the long time scales which characterize the climate, there is a clear need for long series of measurements. Unfortunately, such measurements are not available with the degree of accuracy required to clearly evidence the main causes and infer the possible mechanisms of influence. For example, total irradiance and spectral irradiance can only be properly measured from space and are available only since the beginning of the space age and more precisely since the mid 1970's. For the reconstruction of past climatic variations, the recourse to proxy data is absolutely necessary; with of course the problem that the accuracy is worsening the further in the past one wants to go. For the future, space missions will prove to be invaluable in providing the most critical of these data. There is however a concern that future international plans are not securing the long-term continuity required to properly understand the Sun-Earth connection and to forecast the effects of solar dynamics on our living environment.

3.1 Solar influence on the magnetosphere: Cluster and Double Star

The solar wind has a very clear influence on the magnetosphere and the ionosphere. Magnetospheric convection is driven by the solar wind through the merging of the interplanetary magnetic field with the magnetospheric field at the magnetopause level, and reconnection in the tail. Substorms are the response of the magnetosphere and ionosphere to enhanced energy input from the solar wind which controls some of their global features such as the formation of the thin current sheets. However, large solar wind inputs are not necessarily inducing large substorms, and the local conditions are often prevailing above external influence. Multi-points measurements such as those made by the four Cluster satellites and Double Star are therefore crucial for the understanding of these interactions (Fig.3). As far as the ionosphere is concerned, it represents one of the main sinks of the solar wind energy through coupling of mass, momentum and energy to the magnetosphere [5], [6].

3.2 How does solar radiation influence the Earth

The Earth's distance to the Sun and the Earth axis obliquity have proven through the Milankhovitch cycles the existence of solar forcing [7]. Total Solar Irradiance, TSI, is the main power for the Earth and its atmosphere. Cut off the Sun and the Earth will not be warmer than Titan! However, the TSI is remarkably constant within a few tenths of a %, even on climate time scales (Fig.4). An increase of 0.1% corresponds to only 0.24 watts per square meters equivalent to 5 years of increases of green house gases forcing, at the present rate. Therefore, it is small! Furthermore, the oceans thermal inertia tends to smooth out any short term fluctuations. Over longer time scales, TSI changes, if they do exist, may contribute to climate forcing but our knowledge of the mechanisms which may produce such changes is limited by our coarse understanding of the detailed internal solar machinery!

Precise measurements of TSI variability can only be obtained from space, and any secular change can only be estimated through proxies [3]. Understanding the role of solar forcing in the overall climate changes is not simple. Several causes of forcing are at play at the same time: solar, volcanic, anthropogenic… That "degeneracy" of the solar influence however, does not rule out the evidence that solar forcing has caused a continuous increase in the Earth temperature since the early 20th century, but also that anthropogenic forcing seems to be the strongest cause of global change in the present times. Whether this 20th century TSI increase has any relationship with the already mentioned increase of the open solar magnetic field has not been proven yet. Again, more remains to be understood of the solar phenomena underlying magnetic field and TSI variability!

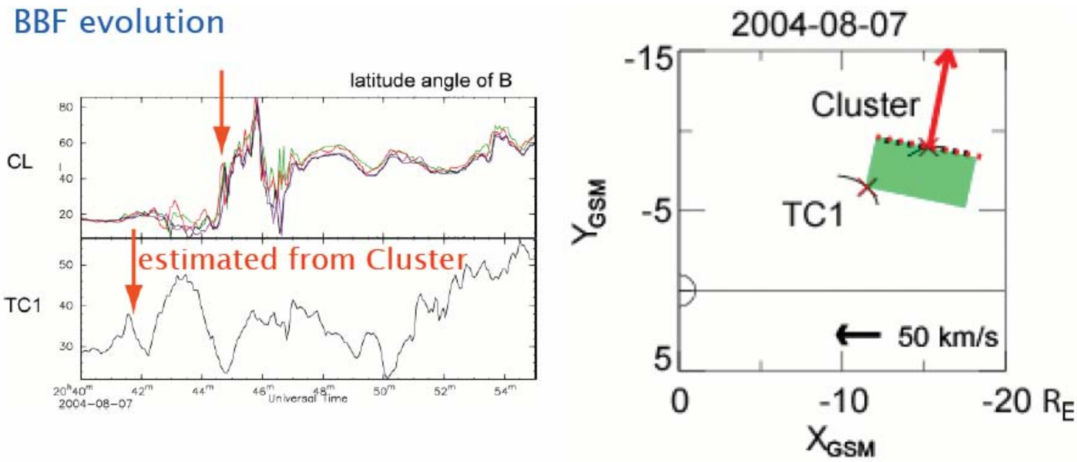

Fig.3. Large scale current sheet dynamics: example of tailward/dawnward propagation of depolarization as observed by Cluster and Double Star (TC1) at substorm onset [5].

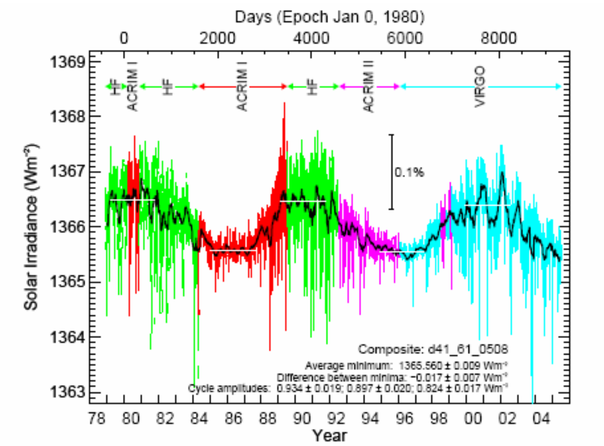

Fig.4. Composite of the variability of the Solar Constant (TSI) over the period 1978-2005 by the PMOD team in Davos [1]

Although UV radiation provides less than 1 % of the total irradiance, it is responsible for more than 50% of the total irradiance changes over a solar cycle. The more energetic UV photons do not reach the Earth's surface because they are absorbed by the atmosphere. Consequently, they do not have a direct effect on the global surface temperature. However, they do influence the composition, the temperature, and the dynamics of the upper atmosphere. The temperature in the high thermosphere varies in phase with solar activity [8]. Evidence seems to grow that coupling to the lower atmosphere may have an influence on the local and global climate [9], [10].

3.3 The Sun and the ozone layer

Fig.5. [10] compares the solar spectral irradiance as measured at the top of the atmosphere and at the surface. The absorption bands in the infrared are due to the presence of water vapor while the complete extinction at wavelengths below 300 nm is essentially due to ozone. This observation obviously shows that solar UV variability has an effect on the ozone layer. Due to the high sensitivity of that layer to anthropogenic industrial activities, it is of crucial importance to understand how solar phenomena might influence its physical, chemical and dynamical characteristics.

Besides direct absorption of UV radiation, the ozone layer is also influenced by solar particles, in particular the Solar Proton Events (SPE). The GOMOS instrument onboard the ESA ENVISAT mission and the Swedish ODIN satellite, have observed a strong depletion of stratospheric ozone – as well as a simultaneous increase in the concentration of NO_{2}-- above the Artic after a strong burst of SPE on 28 October 2003 [11], [12].

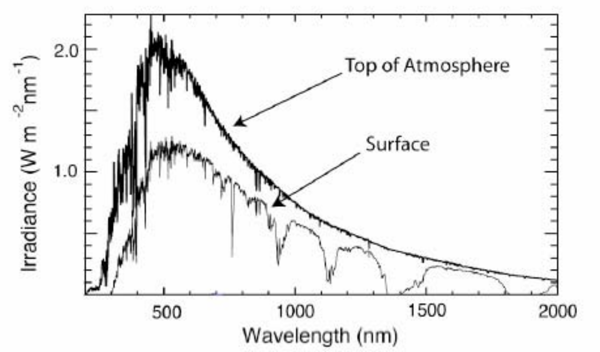

Fig.5. The solar spectral irradiance at the top of the atmosphere compared with irradiance at the Earth's surface. The strong absorption bands in the infrared are due to water vapor and the complete extinction at wavelengths below 300 nm is due to ozone [10]

3.4 Galactic Cosmic rays

Galactic Cosmic Rays have been made responsible for nucleation effects and on the formation of clouds [13]. Even though they do penetrate into the Earth's atmosphere and are able to produce through nucleation, particles in the size range of a few nanometers [14], whose number density is modulated by solar activity, there is yet no clear evidence that cloud formation in the Earth atmosphere, at altitudes of 4 to 10 km, is influenced by solar activity [15].

4. FORECASTING SOLAR ACTIVITY

Due to its strong influence, it is important to be able to forecast solar activity through all its manifestations: solar wind, Coronal Mass Ejections, Solar Proton Events, UV radiation modulation by magnetic activity and of course ultimately, magnetic activity itself and strength of the magnetic cycle. Even though many areas of ignorance do remain, important progress has been accomplished in the past ten years, in particular thanks to a better knowledge of the solar interior.

Helioseismology, with its capability of probing underneath the solar surface, has revealed the complexity of the internal rotation and of the dynamo mechanism, evidencing our poor understanding of the generation of the magnetic field. Down to the tachocline –the layer separating the radiative zone from the convective zone- , the rotation shows changes over periods of only a few months which are very difficult to reconcile with the 11 years cycle. One of the reasons of our poor understanding, despite the proven diagnostic power of Helioseismology, is to be found in the difficulty to observe at high heliographic latitudes above the magnetic poles and along the magnetic axis, since all Helioseismology observations are conducted from the ecliptic plane, with a resolution which is not sufficient to properly analyze the large and small scale motions in areas where the solar magnetic dipole reaches the surface [16].

Nevertheless, the GONG network and SOHO in particular have provided powerful diagnostics of sub-photospheric layers underneath active regions, making it possible to look at the various stages of their life cycle [17]. The building up of active regions covers an extended period of time. There is no single large structure that could reveal that an active region might eventually appear, but rather a continuous emergence of relatively small scale structures that gradually converge to create the active region. The roots of these structures may extend deeper than 80 Mm. Even though there is no obvious signature in the velocity field prior to emergence, it appears that the energy release sites of major active regions are associated with strong shearing and converging flows at shallow depths, 4-5 Mm below the surface.

More accurate observations will yield flow maps with higher temporal and spatial resolution, providing an observational tool that hopefully will allow to forecast some of the most energetic particle and acceleration sources appearing at the solar surface. They will also provide useful information on the linkage between the interior dynamics and the coronal magnetic fields.

Recent progress in acoustic holography [18] has allowed the observation of sunspots and active regions on the hidden side of the Sun: a sunspot or an active region group reveals itself because it possesses very strong magnetic fields that slow down the sound waves. In this way, one may be able to forecast the appearance of the strongest and most active of these structures before they do show up on the visible surface.

Some coronal structures are more likely to erupt and to trigger Coronal Mass Ejections. This is the case of the so-called “sigmoïd” structures that have been identified on X-ray images of the corona obtained with the Japanese Yohkoh mission [19]. Magnetic reconnection inside these structures can release more than half of the magnetic free energy initially stored. However, forecasting the geo-efficiency of CME’s is rather difficult after they have been detected on the Sun.

5. CONCLUSION: THE NEED FOR A MORE COHERENT APPROACH TO THE SUN-EARTH RELATIONS.

It is our hope that evidence has been given above that Sun-Earth relations must be properly analyzed in order to understand better the natural forcing and influences of the Sun on our planet, its magnetic environment, the way its atmosphere is able to transfer solar energy from the top downward. These relations must be studied in a more systematic and coherent approach than in the past. Having organized the set of already existing international solar physics and magnetospheric missions between the respective agencies, as was done with the NASA ISTP and the ESA STSP programs, has been a major progress. Our understanding of both solar physics *per se* and the way the Heliosphere and the Earth react to solar activity improved considerably. At the same time, the perception arose that more ought to be done to overcome the inherent complexities of a system where chaotic and amplification factors seem to play a crucial role. The regrouping of the ISTP missions into what might be called an opportunistic program, has been a long but nevertheless successful process which culminated by the adjunction of new missions from Russia (Interbal) and last but certainly not least, of the two Chinese Double Star satellites that perform beautifully since their successful launch in 2003 and 2004[1]

The next step will see more missions and new participants involved through the establishment of requirements and of a road map with the aim of considerably improving our understanding of the global Sun-Earth system. With that goal in mind, NASA has proposed to create its Living With a Star program. In 2000, its international partners have offered to internationalize the program which is now called ILWS. At a time when the future of our planet is a topic of concern, and at the eve of celebrating the first 50th anniversary of the birth of the space era, the existence of that program is both symbolic and important. Europe and ESA should maintain their key role in this new program since they have been the driving force of the ISTP. It would be regrettable, to say the least, that this leadership role be sacrificed through the abandonment of their future solar physics missions.

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[1] The incorporation of the Double Star mission in the ESA STSP program is the result of a curious process. In the framework of building its Cluster Science Data Center, ESA released a world wide Announcement of Opportunity with the aim of opening STSP to new international partners. To its surprise, the Chinese Science Academy responded and later proposed to add the Double Star satellites as a complement to the fleet of the four Cluster spacecraft. In 1987, the principle of incorporating Double Star in the ESA program was agreed. The success of Double Star proves the rightfulness of this decision and also the maturity of the Chinese scientists who have clearly proven their ability to participate in major international programmes.

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