Space weather activities in Europe

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Abstract. The Sun has long been understood as a source of energy for mankind. Only in the more modern times has it also been seen as a source of disturbances in the space environment of the Earth, but also of the other planets and the heliosphere. Space weather research had an early start in Europe with investigations of Birkeland, Fitzgerald and Lodge, ultimately leading to an understanding of geomagnetic storms and their relation to the Sun. Today, European space weather activities range from the study of the Sun, through the inner heliosphere, to the magnetosphere, ionosphere, atmosphere, down to ground level effects. We will give an overview of European space weather activities and focus on the chain of events from Sun to Earth.

Index Terms. European activities, heliosphere, solar wind, space weather.

1. Introduction

European scientists have been studying space weather for centuries. Edmund Halley observed that the aurorae were aligned with the Earth's magnetic field (Halley, 1714). Carl Friederich Gauss developed magnetometers together with Wilhelm Eduard Weber to measure the Earth's magnetic field and its variations as part of Humboldt's worldwide web of magnetometers. Samuel Heinrich Schwabe (1844) discovered the 11-year solar cycle and Sabine and Wolf independently linked it to geomagnetic disturbances (Sabine, 1852; Wolf, 1857) and Carrington (1860) identified the famous white light flare and linked it to a geomagnetic storm that occurred the day after the flare. Fitzgerald and Lodge suggested a corpuscular radiation from the Sun (Fitzgerald, 1892; Lodge, 1900). Kristian Birkeland was probably the most public-outreach effective space weather scientist, as he reported results from his expedition to the auroral zone to the Norwegian daily newspaper “Aftenbladet” which also sponsored his travel (Birkeland, 1908).

While there are no coordinated European Space Weather activities as such today, Europe has contributed a lot to our current understanding of the physics underlying space weather. In this spirit, this paper does not give an exhausting account of European activities – that would only risk forgetting and leaving out some important activities – but will try to summarize some key observations that go to the heart of the physics underlying space weather.

Section 2 summarizes some key results of ongoing European space missions, some of which were reported at this conference. Section 3 gives an account of a few selected European space weather and space climate activities, while Section 4 describes future activities – planned and envisioned.

I will not consider ionospheric and atmospheric science, not because I don't find it important, but because I do not know the field. An overview of the relevant physics is given by Prölss (2005).

2. Space-weather-related science highlights from ongoing science missions

The Solar and Heliospheric Observatory (SOHO) is certainly ESA's flagship in space-weather research. The long nearly uninterrupted time series of high spatial resolution measurements of solar oscillations has led to dramatic improvements of models of the solar interior. This leads to what is probably the most fundamental aspect of space weather, the solar dynamo which drives solar dynamics, the varying magnetic field, and the solar wind. The release of stored magnetic energy in coronal mass ejections (CMEs) is its most dramatic manifestation. The dynamo-generated magnetic field is the driving agent for accelerating the solar wind. Particles accelerated to high energies in flares and at CME-driven shocks are important consequences of magnetic field reconfigurations.

We have heard, at this workshop (Hill, 2006, this volume), of the new possibility of local helioseismology, with which it is now possible to watch sub-surface domains of the Sun and to follow the emergence of new active regions (Schüssler, 2005). Once this newly emerging field of science has matured sufficiently, we will have figured out another piece of the prediction puzzle that can be used in forecasting interplanetary CMEs (ICMEs) and their geomagnetic effects.

Our predictive capability for the orientation and handedness of CMEs has improved dramatically in the past decade. While the work of Bothmer and Rust (1997) and

Bothmer and Schwenn (1998) was already successful at predicting, at a reasonable confidence level, the orientation and handedness in in-situ data, newer work has succeeded in linking these important properties already in halo CMEs (such as the one pictured in Fig. 1), thus increasing potential warning times from less than an hour to 24 hours - 48 hours and more (Bothmer, this volume). For a review of (I)CMEs see Kunow et al. (2006).

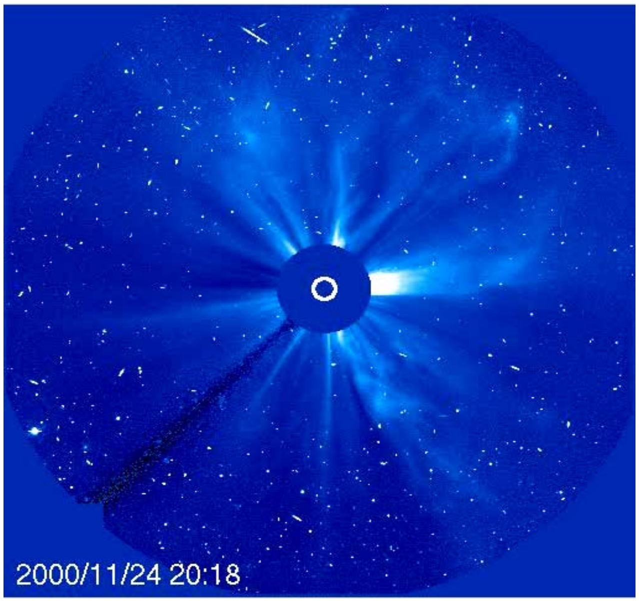

Fig. 1. The November 24, 2000, halo CME. (credit SOHO/LASCO)

However, space weather is not only about CMEs and ICMEs. Several other factors play roles of similar importance. One of them is the solar wind itself which serves as the transporting agent for all particle or magnetic space weather disturbances. Where does it originate and how is it accelerated? While it has long been known that the slow wind originates in or around the streamer belt (Borrini et al., 1981; Feldman et al., 1981), it took more than a decade to decide that it must flow around the edges of the streamers (Wimmer-Schweingruber, 1994; von Steiger et al., 1995; Raymond et al., 2001). Similarly, the fast solar wind has long been known to originate in coronal holes (Nolte et al., 1976), but it took two decades to link its origin to the chromospheric network (Hassler et al., 1999) and explain where the acceleration sets in (Tu et al., 2005; Marsch, this volume).

Several of the scientific highlights of Ulysses are relevant to space weather. For example, Fig. 2 shows that energetic particles were observed at much higher heliographic latitudes than could possibly be coupled to the accelerating mid-latitude corotating interaction regions according to the prevailing Parker model of the interplanetary magnetic field (Simnett et al., 1995). This can be interpreted in several ways, an extension of CIRs to higher latitudes than previously believed (Roelof, 1995), extensive cross-field diffusion in the solar wind presumably due to random footpoint motion of the magnetic field (Jokipii, 1995), or the organized footpoint motion suggested in the Fisk model of the interplanetary magnetic field (Fisk, 1996). This has implications on how energetic particles propagate through the heliosphere and hence on their influence on space assets. Another example is the much smaller latitudinal gradient in the intensity of galactic cosmic rays than expected before Ulysses (McKibben, 1995). This has greatly improved our knowledge of the modulation of the most significant long-term radiation hazard in interplanetary space.

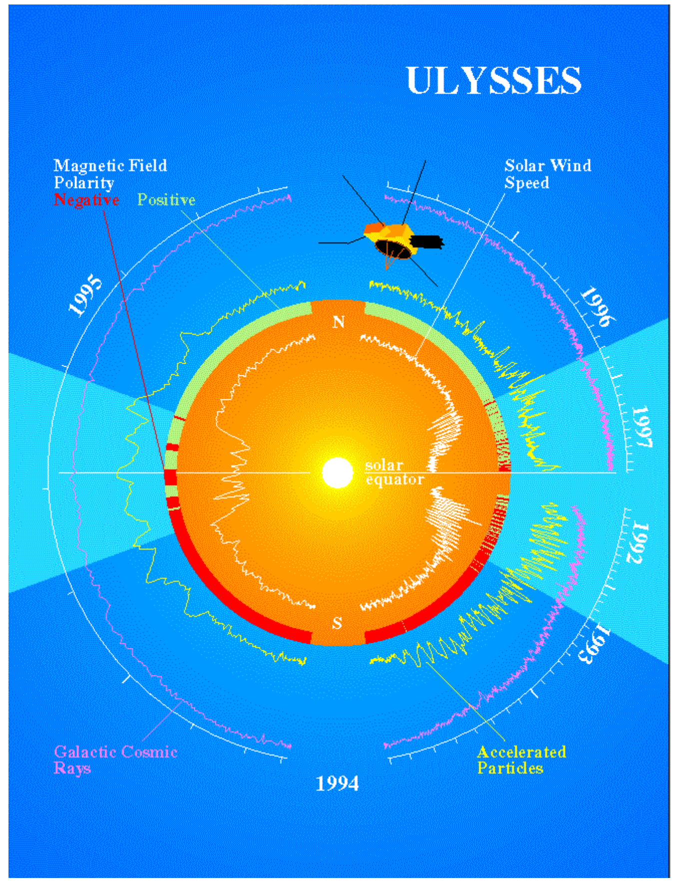

Fig. 2. Ulysses revolutionized our understanding of the 3-dimensional global structure of the heliosphere. One key aspect for space weather is the propagation (and the ensuing modulation) of galactic cosmic rays and the transport of energetic particles in the heliosphere. The pink curve shows the remarkably constant intensity of the GCR throughout the heliosphere, whereas the yellow curve shows that energetic particles reached very high latitudes which were not magnetically connected with the accelerating corotating interaction regions (CIRs) shown by the slow wind alternating with high-speed streams (innermost white curve).

At a much smaller scale, Europe's first multi-spacecraft mission, Cluster, is ideally suited to disentangle spatial from temporal effects and thus to determine the true orientation of discontinuities and shocks in the solar wind and magnetosphere. Furthermore, the four spacecraft allow the determination of currents in the magnetosphere by the curl-B method (Dunlop et al., 2002a). Moreover, the previously used single-spacecraft minimum-variance analysis method for determining normals to discontinuities was found to be considerably less reliable than widely believed (e.g. Dunlop et al., 2002b). This has implications for shock acceleration of particles where different mechanisms are believed to be at work in (quasi) perpendicular and parallel shocks. Usually,

θ_{Bn} is determined using this single-spacecraft technique for obvious reasons, but the classification of the shock could be faulty more often than previously estimated.

One of the key findings of Cluster was the recurrent observation of reconnection events in the magnetosphere (e.g. Phan et al., 2001). Combining Cluster observations with those of the Chinese Doublestar mission has resulted in a first "multiscale" mission and led to the discovery of a reconnection and the associated accelerated particles (Dunlop et al., 2005) and the oscillation of the magnetotails neutral sheet over an extent of 30000 km (Zhang et al., 2005).

The previous examples show than "many eyes see more than one" and that the scientific requirements of space weather and ILWS – as incompletely defined as they still may be – can only be met if multiple measurements are combined, if the data from ongoing missions are utilized in a coordinated manner.

Long-term space-weather effects have been termed space climate and have received renewed attention in the past years. The long-term total solar irradiance measurements by the VIRGO instrument (Fröhlich et al., 1997) on SOHO have driven home the point that the Sun is a variable star, albeit at a low level of variability (~0.1%), at least in the visible range of radiation (von Steiger and Fröhlich, 2005). However, solar EUV irradiance can vary by an order of magnitude or more on short time scales and by a substantial factor over the solar activity cycle (Lean, this volume). The same is true, but with even greater variability, for solar X-rays. The latter two are an important input for ionospheric physics and thus highly relevant to space weather. Even longer term changes to solar irradiance, on the order of several solar activity cycles, are a subject of intense debate. Using ^{14}C and other GCR-induced radio-isotope tracers, Lockwood et al. (1999) and Solanki et al. (2000) have succeeded in reconstructing what they believe to be total solar irradiance in the past. The intensity of galactic cosmic rays is modulated by the heliospheric response to solar activity. In the Earth's atmosphere, these high-energy particles produce spallation products, e.g. the radioisotope ^{14}C and others. These rare isotopes are incorporated into terrestrial archives such as trees (with tree rings allowing temporal reconstruction) in the case of ^{14}C or in air bubbles in the stratified antarctic ice shield. After correcting for various effects such as temperature-dependent incorporation rates (e.g. by using the $\delta^{18}O$ method), these archives can be inverted to deduce solar activity back to times when no records were kept. Remarkably, there appears to be a non-negligible influence of solar activity on the climate of Earth. This could be due to a variation in total solar irradiance (as favored by Usoskin et al. (2004, 2005)) or to the influence of solar EUV and X-rays on the conductivity of the Earth's atmosphere and ionosphere, or even to the GCR itself. Marsh and Svensmark (2003) have proposed that GCR may have an important influence on cloud formation in mid altitudes, probably by ionizing aerosol particles which in turn serve as condensation sites for cloud droplets. Such clouds have a cooling effect on terrestrial climate by increasing the Earth's net albedo. Vahia (this volume) puts this discussion in the context of even longer time periods, where the Sun's journey through the Galaxy needs to be taken into account.

This lengthy example of a space climate issue demonstrates how complex the issues of space weather and space climate are and how this topic needs to be considered in a truly interdisciplinary manner. While this is part of the beauty of space weather/climate science, it also lies at the heart of our difficulties to adapt to the needs of space weather. We were taught, during our professional training, to solve problems - preferably on our own if we wanted to pass an exam. In space weather studies, we will not solve the real problems by making one very clever measurement and interpreting it ourselves. Too many factors are important in the complex Sun-Heliosphere-Earth system and nobody can possibly understand them all, making collaboration across disciplines a necessity for ILWS.

3. An assessment of European space-weather activities

In Europe, ESA member states are responsible for the science activities in ESA's science program, while ESA provides the mission, spacecraft, operations, etc. Member states provide support for the development and exploitation of instruments for space. Space weather activities in Europe also fall under the responsibility of the member states. ESA has no mandate to lead a European space weather office similar to the Space Environment Center (SEC) at the United States National Oceanic and Atmospheric Administration (NOAA). As a consequence, space weather efforts in Europe are largely uncoordinated and rely on ordinary scientific communication and coordination channels.

On the other hand, inspite of the estimated cost of space weather effects to the European economy of 50–100 million Euros per year, the European market for space weather is not strongly developed (Shaw and Howes, 2001). This is remarkable, as the space sector is highly competitive and space weather forecasts are likely to increase in importance because of the miniaturization of electronics components, the desire to drive systems closer to their margins and to cut manufacturing costs of space systems.

The difficulties that space weather activities in Europe are facing basically boil down to two problem areas (Flynn, 2001):

1) Space weather products are defined by the science community with little regard for the needs of their potential customers.
2) Customers are not willing to pay for space weather data products.

Space weather products are defined by the science community with a focus on the fundamental science associated with space weather. For instance, the success of SOHO aiding to understand the solar dynamo that is ultimately responsible for the energy supply to the solar wind and to coronal mass ejections is hardly relevant to a company that is studying the kind of radiation shielding needed for a satellite it wishes to launch. The science community and commercial, governmental, and military customers do not speak the same language and do not have the same priorities for space weather. Much of the difficulty in communication between scientists and customers is probably also due to the increased pressure on scientists to find societal relevance for their research. All of a sudden, previously obscure dynamo theory is presented as highly relevant for space weather. Yes, it is for the underlying physics, but it is not for space weather customers. They do not want to see that data, they couldn't care less about α and ω dynamos and where the overshoot region needs to be situated.

Customers are not willing to pay for space weather data products, but are willing to pay for the service of “translating” the science-driven data to their needs because there is a glut of data available and potential customers do not have the resources and scientific background to weed through it to find what they need (Flynn, 2001).

In spite of this glut of data, several customer wishes are not satisfied. Among them are: The timely provision of data at non-standard time intervals (i.e. time intervals that suit the needs of the customer) and higher cadence (few minutes), the timely provision of good ionospheric data (e.g. closely spaced total electron content data every few minutes), more solar wind data, and better forecasts (Flynn, 2001).

Inspite of this somewhat negative summary of European space weather activities, Koskinen and Pulkkinen (1998) highlight that Europe does have world-leading scientific and engineering competences in solar terrestrial physics, modeling of space-weather phenomena and effects on the space environment. Much of this leading expertise is a consequence of ESA's science program and its missions such as Ulysses, SOHO and Cluster. With the dearth of upcoming missions in the solar-terrestrial field, it is by far not clear that this leadership can be maintained in the future. An additional difficulty in this respect is the wave of retirements of experienced researchers and engineers in European institutions coupled with the rigid European labor laws. We are in a race to maintain our expertise before it retires and we desperately need new missions to train the next generation of space (weather) scientists and engineers. Given the financial state of European member states, this will require a less expensive way of developing and running missions.

Based on these observations, I would be inclined to make the following inexpensive recommendations for space weather activities in Europe. The first action to take is to increase the awareness in the scientific community about the needs of their space weather customers. This is not easy, as there is no agency who is responsible for this. There have been several space weather workshops in Europe in the past years (since 1998), however, searching through their program and/or proceedings web pages, I could not find a single mention of the word “customer” in the titles of sessions or talks.

Second, we scientists need to package information according to our customers needs. For this we need to listen to them and try to understand their language. While this sounds like an obvious task, all the material I looked at while preparing this work says that this is not happening. This problem is not unique to Europe.

Third, we should group together several institutions into “centers of expertise”, which can exchange students for advanced courses, organize joint summer schools, and who exchange graduate students for parts of their PhD work. This would increase the chances of maintaining our expertise in a wide base of young researchers. An example of such an initiative is the newly emerging Nordic Graduate School in Space Science (NGS^3), a loose informal group of European institutions offering graduate and undergraduate studies in space or extraterrestrial physics (see www.ieap.uni-kiel.de/et/lehre/ngs3/ for more information).

Alternatively, we could develop one or two (or as many as it needs in Europe) common European space weather course for Masters level education, possibly using material developed by the Nordic states who are more active than the rest of Europe. This again would serve to train young researchers in the field and thus maintain European expertise.

4. Future space weather science needs

A viable effort to be able to forecast space weather at Earth and other locations (e.g. Mars and the Moon) will need to proceed in four steps – monitoring, forecasting on a best effort basis, understanding the important effects before finally forecasting on a operational scale.

Monitoring: SOHO and ACE (the Advanced Composition Explorer) are currently monitoring space weather ahead of Earth. Both are ageing spacecraft, and potentially prone to failure anytime, as is exemplified by the SOHO vacations and by the "keyhole" data gaps due to orbital constraints of both spacecraft. Once launched and operational, the Chinese mission KuaFu (Tu et al., this volume) may serve as a replacement for SOHO and parts of ACE.

Forecasting I: The combined remote-sensing and in-situ observations will allow crude forecasting on a best effort basis, comparable to the SOHO and ACE near-real-time data efforts (see e.g. Zwickl, this volume). This "forecasting" resembles weather forecasting on Earth based on the kinds of clouds that are currently in the sky – e.g. cirrus uncinus announce rain within 48 hours. As accurate as this empirical method may be, it is unsatisfactory from a scientific point of view as there is no understanding of the underlying processes involved, it would rely on a very large number of “weather stations” and would still give insufficient warning.

Understanding: This necessary understanding of space weather processes needs to be addressed in the third step, but probably implies a fleet of spacecraft throughout the inner heliosphere and possibly beyond - depending on the goals that space weather forecasting needs to fulfill. Space weather encompasses phenomena originating in the Sun and ending on Earth's (or Mars' or the Moon's) surface. The scientific aims will certainly involve understanding the solar dynamo, and hence the global flows of plasma in the entire solar interior, including the polar areas. This will be explored by ESA's Solar Orbiter and may be addressed in a more fundamental way by a Solar Polar Orbiter, currently envisioned in ESA's Cosmic Vision 2015-2025 program. Understanding the onset and outbreak of CMEs and the origin of the various solar wind types will be addressed by NASA's STEREO and SDO missions, while their interplanetary manifestations, ICMEs, will be investigated in-situ by Solar Orbiter and NASA's Sentinels. These will also further our understanding of particle transport in the inner heliosphere and address questions such as why not all shocks accelerate particles (e.g. Lario et al., 2006). Once disturbances arrive at Earth, they couple into the Earth's magnetosphere, ionosphere, and even atmosphere. This cross-scale coupling is inherently difficult to understand because so many different scales are involved; AU-sized ICMEs drive magnetospheric currents carried by electrons which interact on their own inertial length, orders of magnitude smaller than the ICME. Some multi-scale mission will need to address this coupling, ESA's Cluster has just shown us the richness and difficulties of observations that will be involved. The coupling to the ionosphere could already be investigated at a comparatively low price, but this is hindered by economic and military interests. For instance, total electron content measurements are hard to find, at least in Europe, because they are commercially controlled, but would be of great forecasting value. Further progress will come from comparing different magnetospheres (Mercury with BepiColombo, Earth with Cluster, Mars with MarsExpress and following Mars missions, and Jupiter`s with piggyback instruments on future Jupiter missions). The galactic cosmic ray background is the most important long-term radiation hazard that will be encountered by astronauts on future interplanetary missions. Therefore, its modulation needs to be understood on a more firm footing, especially the influence of the heliosheath and heliopause region are considered to be important but badly understood agents in this respect. A Heliopause Explorer Probe, such as envisioned in ESA's cosmic Vision 2015-2025, would address how the heliosphere shields us from the hostile interstellar environment and how this may have been different in the past, possibly affecting space and Earth's climate. Space weather "stations" at Mars and other "outposts" may be necessary, as will be radiation measurements on planetary surfaces, such as MER's MARIE, MSL's RAD, and ExoMars's IRAS radiation monitors. Needless to say, this large observation effort will need to be met by a massive effort in modeling and coordinated data analysis. This will require that sufficient qualified scientists are working in the field during this great era of understanding and drives home the point made in Section 3 that we need to train this generation now.

Such a comprehensive space weather program will necessitate a rethinking of the way NASA and ESA run their missions. Both agencies will have to find ways of greatly reducing the cost of their space missions. Probably this can only happen by accepting more risk and by reducing complexity of spacecraft and missions. They will also not be able to handle such a heavy mission operation load, and there will be an urgent need for international cooperations.

Forecasting II: At this point, we should know what is needed to implement an operational space weather system that is able to make forecasts that satisfy the needs of most customers. Presumably this will involve a massive modeling/computing effort on the one hand, and a fleet of minimally equipped spacecraft at strategic locations in the heliosphere or on cleverly chosen orbits. The goals of the space weather system will determine the effort to which we need to go. A system that covers the Earth and Mars will have to look different from one that only covers the Earth-Moon system. Obviously, such a system will be beyond the capabilities of Europe or ESA alone and we will have to cooperate with other nations with similar interests. Let's hope that space weather will work better than the International Space Station and that science will prevail.

Let me end this chapter by continuing with our analogy with weather forecasts on Earth. The operational space weather system will very probably consist of a minimal number of spacecraft and other assets, just as the number of weather stations in Europe has decreased significantly in the course of the last century. Let's not kid ourselves, the Understanding phase will be our only chance for a “Golden Age” of space weather sciences – and we may well be at the beginning of it.

5. Summary and conclusions

Space weather studies in Europe have a long historic tradition begun by Gauss, Schwabe, Birkeland, etc. In spite of this early start, European scientists have not been keen on studying space weather as an applied science with a substantial economic impact. Two points make space weather operations difficult in Europe, the lack of communication between scientists and customers, and the lacking will of potential customers to pay for this service.

Space scientists in Europe have, however, made large important contributions to the science underlying space weather, beginning with helioseismic sounding of the solar interior all the way out to the modulation of galactic cosmic rays by the heliosheath region at the boundary of the heliosphere. Ulysses, SOHO, and Cluster have contributed by allowing the key measurements to be made, as have other nationally led missions or international collaborations. However, it is important to note that these contributions have had such an impact because they are part of an international effort to understand our changing environment in space.

While much more effort is now being put into space-weather activities in Europe, they are often uncoordinated and even more often do not meet the needs of potential customers. Two key problems need to be overcome before space weather becomes a viable economic factor in Europe. First, space weather activities are science driven and we scientists do not normally speak the same "language" as our potential customers. Second, our potential customers are not willing to pay for the space-weather services we would like to supply them with. A way out of this dilemma can only lie in the scientific community listening to their customers and providing them with the products they need. This does not necessarily need to be expensive, some modest changes to the way the information is presented could make a large difference but must be tailored to the needs of the customers. Nevertheless, it is by no means clear that European customers would then switch to European providers and not continue to obtain their information from SEC/NOAA.

An important matter of concern not only to space weather but to all of solar-system science is the lack of upcoming mission opportunities, mainly driven by the insufficient funding of the national and of ESA's science budgets. Space weather is often seen as a means to improve this situation. However, this will not happen if we do not soon learn to communicate more effectively with the general public, politicians, and our potential customers. We also need to learn this soon – before the carriers of European know-how have all retired.

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