"The Grand European Heliospheric Observatory" An integrated ESA approach to challenges in Solar and Solar-Terrestrial physics.

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Abstract

This short document is being submitted to the ESA White Paper exercise for Voyage 2050 missions, though it is perhaps not a white paper in the traditional sense. Rather than focusing in detail on a particular science area, our document is a suggestion that the future ESA science programme should take a holistic and balanced view of the scientific disciplines which underpin space weather, these being solar, heliospheric, magnetospheric, ionospheric and thermospheric physics. Each of these science areas individually justifies its own place in a future ESA Science Programme, though at the terrestrial end of the process chain there is scope for strategic overlap with the ESA Earth Explorer programme, as well as for creative arrangements to facilitate the combined use of ground-based instruments. We believe that, when future missions in the areas of solar and solar-terrestrial physics are considered, it would be appropriate to ensure that a reasonable balance is maintained across the sub-disciplines listed above.

This could, of course, be done by the selection of more than one such mission at various points during the Voyage 2050 programme. An interesting way of achieving the same outcome, however, might be the creation of an ESA L-class opportunity that combined multiple missions from across the fields of solar, heliospheric, magnetospheric and ionospheric physics. Such a concept would not only address major challenges in the Solar-Terrestrial physics, but also underpin the European space weather applications which derive from it. Although these are supported elsewhere in the ESA programme (e.g. in the Space Situational Awareness programme), this is not necessarily done in a way which allows fundamental underpinning research. An L-class opportunity, combining multiple science missions in the way that we are suggesting, could provide the framework for an integrated and collaborative approach to constitute a “Grand European Heliospheric Observatory”.

Introduction

Space weather should really be understood, not as a science area in itself, but as an application of science, bringing together knowledge from across multiple scientific disciplines (the obvious ones being solar physics, heliospheric physics, magnetospheric physics, ionospheric physics and atmospheric science; but also linking with fields such as materials science and magnetotellurics). This knowledge is used to address the problems of predicting and mitigating the effects of energetic processes, initially arising from solar activity, on human society and its technology, either on the Earth's surface, in its atmosphere or in geospace. While the implementation of space weather observations, models and mitigation strategies tends to be operationally-focused and impact-led, and therefore rightly belongs outside the ESA science programme, the selection of these tools and techniques is underpinned by a huge body of scientific knowledge, which cuts across multiple disciplines.

Thus, while space weather is increasingly regarded as an important societal hazard, as reflected by its inclusion in the civil contingency strategies of multiple countries, there remains a compelling need to advance the underlying science, as this will ultimately enable monitoring, modelling and mitigation strategies to be improved. This underpinning science is not space weather, but consists of basic research into the fundamental physical processes connecting the solar interior with the Earth's environment. As such, it most certainly belongs in the ESA science programme domain, of which it should be an important part, given the already advanced development of the relevant observing techniques and the relative accessibilty of the key regions (when compared to interplanetary missions, for example).

This document is, therefore, an attempt to make the case for a cross-disciplinary ESA approach to advancing the science which underpins space weather. It calls for the adoption of a coordinated approach, to avoid the fragmentation which tends to result when each community individually proposes its own favourite missions, without necessarily considering how these might fit together into a broader picture. We are making the suggestion that ESA, while perhaps stopping short of a formal roadmap, should exercise a strategic approach to mission selection in this area, taking into account the most important areas in which knowledge is still lacking and recognising that addressing such knowledge gaps would not just benefit science in itself, but also the space weather applications areas which depend on such scientific understanding.

It is worth mentioning that this strategy might even extend further than the selection of space missions for the ESA Science Programme. We note that the chain of physical processes underpinning space weather extends far down into the terrestrial upper atmosphere, even down to the Earth's surface. Within the last few years, ESA has brought forward some missions within its Earth Explorer programme with the potential to address scientific questions important to space weather (examples include SWARM and the recent selection of the Daedalus mission). Hence coordination between these two ESA programmes seems very desirable, in order to forward progress in this science area.

We should also mention the fact that, in principle, ESA has the possibilty to contribute funding to ground-based instruments where the use of these would enhance the effectiveness of its selected space missions. While this has not often happened in practice, multiple aspects of the science covered here would benefit from ground-based support, ranging from high-resolution observations by solar telescopes, through radio techniques to measure solar energy release and solar wind propagation, to ground-based radar measurements of the processes connecting the ionosphere and magnetosphere and the eventual dissipation of this energy in the terrestrial atmosphere.

Overview of key science areas

Below we set out, at very high level, ten science areas, which we believe could achieve both significant scientific impact and potential synergistic operational benefits. These benefits to operations would arise, among other things, from enabling scientific progress which drives the development of better modelling and prediction, giving the operational missions e.g. in the ESA Space Situational Awareness programme a better context in which to work. The following text is certainly not intended to be a detailed science case, as each of these areas could justify a "white paper" in its own right. Although we present some very high-level ideas, it is also not the intention of this document to propose new mission concepts, since multiple concepts are presented in the other White papers connected to this exercise. Rather the following is meant as a summary of areas that a balanced programme could potentially address. Such a programme could, of course, be realsed not only through opportunities in Voyage 2050, but by strategic collaborations with other agencies. It is worth noting that, in some of these areas, ESA is or has recently been involved in missions which address parts of this science, though improvement and some level of continuity of observations is highly desirable, not least given the inherent long-term variabilty of the solar-terrestrial system.

1: Long-term modulation of solar activity

The present epoch of solar activity appears to be particularly interesting, as recent solar cycles seem to be displaying a marked decrease in sunspot activity, with possible evidence that the Sun may be entering a new "grand minimum" of activity, on a scale not seen for more than three centuries. While the causes of such "grand minima" remain disputed, historical proxy data for solar magnetic field suggest that these phenomena might recur every 350-400 years, so that the coming grand minimum (if confirmed as such) might be one of a series, the last of which was the Maunder minimum of 1645-1715. Although the mechanisms behind such variability are unclear, an idea attracting interest is that long-period perturbations to the dynamics of the solar interior might change the effectiveness of the magnetic field dynamo, hence inhibiting the emergence of solar active regions to the photospheric surface (see the section on flux emergence below). While this idea remains very controversial, it might potentially mean that observations of magnetic transport and flux emergence made in the interval between now and 2055 (the predicted end of the grand minimum) would provide a very interesting data set for comparison with observations made earlier and later.

Goal	What is the long-term variability of the solar dynamo, what are its causes and how does this affect solar activity?
Concepts	Long-term measurements of solar magnetic field at the photosphere and below. Comparison of "grand minimum" conditions with the behaviour of the "normal Sun".
Mission Scenarios	SDO-type mission(s) in solar orbit, ensuring sustained high-resolution magnetic field measurements of the Sun over multiple solar cycles, especially during the potential "grand minimum". Perhaps consider a mission in solar polar orbit, as a novel complement to existing observations. Magnetic imaging complement to Solar Orbiter, possible replacement for NASA Solar Dynamics Observatory at end of life [M1].

2: Solar magnetic transport and flux emergence

How magnetic flux is transported from the solar interior to the photosphere and subsequently emerges outward into the corona continues to be an active area of research. For the forecasting of space weather effects, it is vital to understand how the precursors of solar active regions develop, before they become visible on the photosphere. This necessitates investigating the dynamics below the photosphere and missions such as SDO are now beginning to offer the prospect of spotting precursor regions a day (or even a few days) in advance of their emergence. The problems of flux evolution, and the continued transport outward to the corona are, however, complex, not least because the boundary conditions are so little known. In addition, the effects of turbulent processes on flux emergence are not well understood and require more investigation. In this area, the application of helioseismology imaging techniques capable of probing altitudes below the photosphere is critical, though there is also an important role for high-resolution photospheric observations, potentially including data from ground-based solar telescopes. Assimilation of high-quality magnetic and photospheric data into current models (such as the NASA ADAPT or EU-funded EUPHORIA models) might be an important route to driving forward progress. In addition there is the intriguing possibility that we may be entering a period in which such transport mechanisms may be becoming anomalously affected by long-period changes in the solar dynamo (see Section 1 above).

Goal	How do active regions emerge from the solar interior onto the photospheric surface and outward into the corona? Are there usable proxies to predict such solar flux emergence?
Concepts	High-resolution measurements of solar magnetic field at the photosphere - as continuous as possible. High-resolution measurements of the magnetic connectivity between the solar atmosphere and the inner corona.

Mission Scenarios	Continuous observations of the same region, potentially over multiple solar rotations, calling for a multi-spacecraft perspective. As in [M1], but potentially with multiple spacecraft e.g. a solar-orbiting ESA magnetic fields mission to complement SDO. Perhaps consider a mission in solar polar orbit, as a novel complement to existing observations. A dedicated mission to map the magnetic connection to the inner corona [M2].

3: The evolution and energisation of the outer solar atmosphere

The challenge in this area is to understand and predict the way in which the solar corona will evolve, starting from a given initial state of the solar magnetic field. This requires an understanding of the factors determining the rate at which solar magnetic flux is transported across the photosphere, and how free magnetic energy builds up in the lower corona, especially in the vicinity of solar active regions. Once again, high-resolution magnetic mapping is required, ideally with coronal data from the same region (perhaps requiring simultaneous observations from a different vantage point). Several groups have been developing 3D models and are beginning to tackle this problem, so that joint approaches involving modelling and data would again be highly beneficial.

Goal	How does the magnetic field and and plasma evolve through the solar atmosphere? How does the magnetic field couple different parts of the outer solar atmosphere? How does the corona become energised and how is its structure determined in active regions, coronal holes and quiet Sun?
Concepts	How and where is free magnetic energy stored in active regions? How is magnetic flux transferred from the solar interior to the corona? High time and spatial resolution coronal mapping of the plasma properties and the magnetic field.
Mission Scenarios	High time and spatial resolution observations of the outer solar atmosphere through imaging and spectropolarimetric measurements in multiple wavelengths. Synergistic high-resolution measurements, targeted using the more global observations from the instruments in [M1] and [M2] above. Could perhaps use the same spacecraft as [M2] in practice, with the focus on high-resolution instruments having a smaller field of view.

4: Energy release in solar flares and CMEs

Eruptive flares and CMEs are the primary drivers of Earth-impacting space weather. A key issue in understanding their genesis is the question of how energy becomes concentrated along narrow filament channels, which then erupt, and why the reconnection in these eruptions is so fast. Highly time-dependent processes are clearly taking place in these regions, in which free energy becomes available very quickly to drive fast reconnection and explosive energy release. An understanding of the overlying coronal structure (and how this is driven by flux emergence) is also critical to quantifying the effectiveness with which the released energy can be communicated into the heliosphere. The question of whether (or to what extent) an accurate model of solar flares can be derived from a good representation of an active region, its adjacent background and the magnetic topology of the corona and closed heliosphere requires a great deal more investigation, likely involving both improved observations and progress in theory and modelling. Another open question is how a solar flare puts so much energy into the production of energetic particles. While exact predictions of Solar Energetic Particles are probably not feasible, given the current level of knowledge, general predictions about the strength of flares and CMEs arising from particular topologies might at least be possible.

Goal	How is energy stored and released in the solar atmosphere?
Concepts	What processes are responsible for triggering the release of energy via solar flares and CMEs? How and where are particles accelerated during a solar flare?
Mission Scenarios	A mission to measure the solar magnetic field, potentially from 2 points, with spectroscopic and high energy capabilties [M3]

5: Particle acceleration and shielding in the solar wind

While the extended solar minimum conditions of recent years are generally marked by the observation of relatively large fluxes of Galactic Cosmic Rays, recent solar maxima have been characterised by some very large SEP events (even in solar cycles with quite low activity peaks). Many of these are associated with large isolated solar flares, with a tendency for SEP activity to continue well into the declining phase of a solar cycle. However, there are suggestions that some of these SEP populations also derive from solar wind shocks which form very close to the Sun (~1 Rs) in regions of appreciable compression. Such solar wind compressions seemingly have the potential to become very large structures which can occupy appreciable regions of the heliosphere. The roles of both shocks and compressions in accelerating particles have been shown in simulations and both are undoubtedly important in the heliosphere; however the understanding of these acceleration mechanisms in practice is made very difficult by the fact that the structure of variables such as density and Alfvén speed is so poorly characterised. The converse of these acceleration processes is the shielding of GCRs arising from the extended regions of open solar flux during solar maximum, again requiring a better understanding of the development of large-scale heliospheric structure.

Goal	Understanding energetic particle energisations and origins especially in the inner heliosphere.
Concepts	Probing the changing structure and dynamics of the inner heliosphere, including variations with helio-latitude, solar wind evolution in structured regions and shock-related energisation of SEPs. Long enough mission lifetime to experience a variety of solar cycle conditions. Investigation of both poles and lower latitudes with sufficient data for a meaningful climatology.
Mission Scenarios	Consider a Ulysses type mission for the inner heliosphere with large energy ranges for the electron and ion detectors. High-cadence magnetic measurements will be very important. Could in principle be the same mission as [M3] above, with additional in-situ detectors, and capabilties for imaging and X-ray spectropolarimetry.

6: Evolution and propagation of solar wind structure

In the past few years, new solar wind models such as ENLIL have greatly improved the prediction of solar wind propagation, to the extent that the model outputs are now (somewhat) usable for forecasting. Nonetheless, accurate predictions of CME arrival still require observational constraint and factors which are not accounted for, such as the presence of solar wind current sheets, seemingly have the potential to cause significant errors. The Holy Grail would be the possibility to remote sense the topology of the solar wind magnetic field, but this is especially difficult given that the sense of Bz (which broadly determines geo-effectiveness) seems to be quite poorly preserved in a highly-structured heliosphere, especially in the presence of large shocks and compression regions. As well as the magnetic structure of the Earth-impacting solar wind, attempts to predict the energetic particle spectrum are potentially of considerable value, but this is again very difficult, for example due to the effects of shocks or interactions between multiple CMEs. While solar wind imaging is important as a constraint to models, in-situ measurements of solar wind structure from multiple spacecraft at different distances from the Sun would seem to be important as a way of characterising the range of solar wind conditions and the extent and timescales of their variability.

Goal	Direct sensing of solar wind density, velocity and magnetic field on or close to the Sun-Earth line – ideally from multiple locations, but appreciably upstream of Earth.
Concepts	Studies of the development of heliospheric structure with distance and consequent effects on the preservation of solar wind characteristics. Explore extent of in-situ correspondence with remotely sensed solar wind parameters (e.g. measured operationally from L5 or L4 as part of the ESA SSA programme).
Mission Scenarios	Consider multiple spacecraft in solar equatorial orbits at different distances (with orbits in harmonic periods to ensure alignment?) with in-situ instrumentation [M4]. The closest spacecraft could include optical and magnetic remote sensing instruments to fulfil some of the aims of [M1] and [M2].

7: Processing of solar flux at the magnetopause

While the driving of the magnetosphere by the solar wind is the primary determinant of magnetospheric processes, the nature and magnitude of the energy transfer between the solar wind and the Earth's magnetosphere are themselves determined by the direction of the Interplanetary Magnetic Field, which regulates the size and location of the region over which magnetic reconnection can occur and the magnetopause can be open. It is very well established that this coupling is significantly more geoeffective for IMF Bz south than for Bz north, with Bz north reconnection being generally characterised by low energy flux into a relatively small area around the cusp region. When the IMF is strongly southward, however, reconnection can occur over a broad region of the dayside magnetopause, with significant energy transfer across the open-closed field line boundary, though IMF clock angle and solar wind dynamic pressure are also significant determinants of energy transfer. There is also a long-standing discussion over whether the whole dayside magnetopause is open during dayside reconnection or whether the reconnection regions are more dynamic, multiple, patchy structures determined by more local boundary processes. The IMF can also influence the dynamics of the magnetosphere through viscous interactions at the flanks, which can be a significant driver of magnetospheric dynamics, especially under IMF Bz north conditions, while during Bz south conditions these viscous contributions are dwarfed by the mechanical and electromagnetic energy entering at the low-latitude dayside magnetosphere. Understanding of this key energisation process for the magnetosphere has been advanced by successive spacecraft in magnetopause-crossing orbits, especially missions such as Cluster where multiple magnetosphere crossings have allowed key insights into the IMF dependence and temporal and spatial structure of reconnection. The key questions are not all closed, however, simply because of the size of the regions over which reconnection can occur and the paucity over which they can be sampled.

Goal	Understanding the location, spatial extent, variabilty and response to solar wind driving of the magnetopause reconnection regions and viscous interactions at the magnetospheric flanks.
Concepts	Where and how large are the reconnection regions under different IMF directions? What are the structures and consequences of sheared and/or overdraped field topologies? What are the spatial and temporal scales of magnetosphere-ionosphere coupling and what are the respective roles of FACs, waves, and energetic particles in this coupling?
Mission Scenarios	A multi-spacecraft large-scale constellation mission to determine the large-scale topology, magnetic connectivity and variabilty of the magnetopause and associated magnetosheath, bow shock and foreshock regions [M5]. Potential use of tracer techniques e.g. on reconnecting field lines to reveal connectivity. This constellation could be the large-separation component of a nested constellation mission, also involving a group of satellites with much smaller separations for the study of more local processes.

8: The energetics and dynamics of the magnetosphere

While it is well accepted that the impact of space weather processes is strongly modulated by the solar wind driving, pre-conditioning and subsequent response of the magnetosphere, the understanding of magnetospheric structure and dynamics again suffers from the paucity with which this large region is sampled. As a result there are significant difficulties in characterising some of its most important phenomena, such as current sheets and disruption regions. Attempts to understand the large-scale behaviour of the magnetosphere are, therefore, severely compromised by the fact that basic regions and processes are so poorly characterised. Another key issue is that key magnetospheric phenomena cannot always be characterised by approaches based on MHD modelling. In situations such as thin current sheets breaking up into multiple plasmoids, for example, kinetic and/or hybrid interpretations have to be used to properly understand the physics. Modelling codes like these are computationally very intensive, which makes accurate real-time physics-based modelling of the magnetosphere very challenging. Ongoing missions with multipoint observations on different scales continue to be needed to drive the understanding of magnetospheric structure and dynamics. Ground-based diagnostics are also of considerable importance, bearing in mind that the high-latitude ionosphere can be considered to act as a screen, imaging the effects of large-scale magnetospheric processes. The use of instrument networks such as SuperDARN to measure cross-cap potential, for example, can be an important indicator of magnetospheric dynamics, while observations of heavy ion outflow (e.g made by an incoherent scatter radar) have the potential to reveal processes driven from the terrestrial end of the chain which can feed back into major effects on the magnetosphere.

Goal	What are the fundamental modes of energy transfer and partitioning in the magnetosphere?

Concepts	By what means do small-scale plasma processes have large-scale consequences? How is energy converted and partitioned across plasmas and fields in different regions of the magnetosphere? What are the spatial and temporal scales of magnetosphere-ionosphere coupling and what are the respective roles of FACs, waves, and energetic particles in this coupling?
Mission Scenarios	A smaller-scale multi-spacecraft constellation to understand the link between electron-scale physics and its impact and dependence on both outer and inner regions of the global system. The same mission concept could also determine the energy exchange between particles and fields in the stretched to dipolar region of near-Earth space [M6]. This could be the inner-scale constellation component of a nested multi-spacecraft system on the Cross-Scale model, with [M5] forming the outer-scale component. Capabilities could be augmented by use of active experiment in the magnetosphere to unambiguously reveal the connection between the magnetosphere and the ionosphere (tracers) – see the same idea for magnetospheric field lines in [M5]. There would be advantage in having a connection to a simultaneous Low-Earth Orbit, multi-spacecraft mission to study the active link between magnetospheric processes and the ionosphere, e.g. a link to [M8] below.

9: The triggering of storm effects

The difficulty in predicting storm effects in the magnetosphere and ionosphere arises from the fact that the underlying processes are highly non-linear and substantially dependent on pre-conditioning. The initiation of storm processes can be directly dependent on the impact of solar wind structures (such as CMEs, CIRs or high-speed streams) on the magnetopause but it is also possible that storm initiation, while ultimately driven by such processes, can be substantially delayed, with relatively small subsequent inputs being enough to drive the system suddenly unstable. Storm effects generally manifest themselves as a series of substorms, driven by instabilities releasing solar wind energy stored in the terrestrial magnetotail, which in turn produce other key signatures in magnetospheric dynamics, including the development of an enhanced ring current and a strong tailward electric field. The dynamics of the ring current make the inner magnetosphere a key region for monitoring the development of storm-time conditions with the ring current moving inward and becoming strongly enhanced before being impulsively depleted as particles precipitate into the high-latitude ionosphere as storm-time aurora. To understand and better predict the behaviour of these impulsive events, multipoint measurements in the magnetosphere are very important e.g. in the tail where current disruption first occurs, but also in the ring currents where stored energy accumulates and can be violently released. Also remote sensing of the storm-time precipitation of magnetospheric electrons and ions into the high-latitude ionosphere e.g. by optical imaging of the northern and southern auroral ovals from satellites in (highly elliptical) polar orbits are important to understand the location, extent and magnitude of storm-time energy release into the terrestrial upper atmosphere.

Goal	What large-scale and small-scale physics is happening in various regions of the magnetosphere at the point where impulsive energy release occurs? What are the precursors and consequences of this?

Concepts	What is the time history of energy release processes? Is there a reliable and reproducible way of determining when the pre-conditions for storm/substorm generation are (close to) being met? What are the locations and time histories of the subsequent phenomena and how predictable/reproducible are these?
Mission Scenarios	The multi-scale magnetospheric constellations proposed in [M5] and [M6] have the potential to contribute very important observations, depending on their orbital parameters, but it should be noted that the [M5] constellation would not spend all of its time in the magnetosphere. Multiple single spacecraft in magnetotail-crossing orbits (if the orbital dynamics are feasible) might be a very interesting method for measuring tail fields, current sheets, plasmons and injection regions. [M7]

<u>10: The energetics and dynamics of the ionosphere and thermosphere</u>

Both scientifically and for practical purposes, being able to make real-time observations of the ionosphere and thermosphere and predictions about their state for a few days ahead would be a significant advance. This goal, however, is presently too challenging, especially at high latitudes. One reason for this is that the ionosphere is strongly driven by the magnetosphere, not just through processes such as particle precipitation and polar cap convection (which primarily affect high latitudes) but also through factors such as penetrating electric fields which can drive anomalies in density and TEC at much lower latitudes. As well as the high-latitude region, the equatorial ionosphere, in the region of the ionisation crests, is also frequently unpredictable and highly structured. In practice, detailed characterisation of the ionosphere is always likely to rely on a mixture of models and constraining data. These include ground-based data e.g. from coherent and incoherent scatter radars, but also in-situ ionospheric data (mainly from US mission such as DMSP, ICON, GOLD) and ionospheric date remotely-sensed from higher altitudes (e.g using techniques like GPS TEC). The most promising route to an improved understanding, especially of highly structured regions, would seem to involve the use of models allowing data assimilation from a variety of sources, verified by additional independent multi-point (often ground-based) data.

Goal	How is energy transferred from the magnetosphere to the ionosphere and how is this energy subsequently partitioned?
Concepts	What are the spatial and temporal scales of magnetosphere-ionosphere coupling and what are the respective roles of FACs, waves, and energetic particles in this coupling? How do phenomena driven from high latitudes produce global-scale consequences through processes such as penetrating electric fields and wind/wave driven transport? What are the effects of the above on the structure and dynamics of the global-scale ionosphere and thermosphere and how predictable are these? What are the relative importance of large-scale and small-scale processes in producing medium-scale structure?
Mission Scenarios	A Low-Earth Orbit, multi-spacecraft mission with multi-parameter in-situ measurement capabilities to study the active link between magnetospheric processes and the ionosphere [M8], capable of in-situ sensing of the tracers produced in [M6].

Summary

This document is not intended to be a "white paper" in the traditional sense. Rather it is intended to spell out a very high-level vision of an integrated approach to missions in solar, heliospheric, magnetospheric, ionospheric and thermospheric physics, bearing in mind the overarching theme of space weather, which links them all. Our rationale is that although space weather is an application and not a science discipline in itself, it nonetheless relies on a large body of scientific knowledge from the multiple disciplines which constitute solar and solar-terrestrial physics. Current applications work within ESA (e.g. in the Space Situational Awareness programme) mainly deals with operational issues in monitoring and modelling, rather than with the advancement of scientific understanding, which can only come from the ESA science programme.

It is extremely important to note that, whilst a number of the missions outlined here, and in more detailed individual white papers in this round, would provide thoroughly new observational scenarios that would advance our understanding of the Sun, the Heliosphere and the near-Earth environment, each of them by themselves only provides a subset of an overall understanding which necessarily needs to be linked.

Hence we propose that one option which could be considered in the context of Voyage2050 would be the instigation of an L-class opportunity that combines one or more missions from the fields of solar, heliospheric, magnetospheric and ionospheric physics in order to provide a Grand European Heliospheric Observatory that not only addresses major challenges in the Solar-Terrestrial physics discipline but provides rapid scientific advances in a holistic approach to sciences that underpins our European space weather requirements for decades to come.

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