## Summary

The main goal of this document is to identify and prioritise the main science questions to be addressed during the next 10-15 years by the UK solar physics community. The UK has many existing strengths in the area of solar physics, giving it an excellent status within the international community. Based on the science goals and the expertise of the UK solar physics community, the resources needed to achieve these goals are identified. Future opportunities and the broader benefits to the UK pursuing research in the area of solar physics will also be discussed.

## Introduction

The Sun is a fascinating and important object of astrophysical research for many reasons. The first and foremost reason is the vast number of amazing physical phenomena the Sun displays. These phenomena continue to surprise us, despite solar physics being a mature scientific discipline. Solar physics has made great progress over the last couple of decades in increasing our knowledge of both the solar interior and the solar atmosphere. With this increase in knowledge, it has become abundantly clear that solar phenomena are on the one hand more exciting, but on the other hand also much more complex than we would have been able to imagine - we observe intrinsically three-dimensional, time-dependent and usually non-linear phenomena on all length and time scales accessible to present day instruments. This poses enormous future challenges for both observation and theory, requiring the use of innovative techniques and methods (ideas here?).

As our closest star, the Sun is essential for our understanding of other stars. This includes all aspects of solar physics from the solar interior (e.g. energy generation and transport, magnetic field generation and transport) to the solar atmosphere (e.g. coronal heating, flares) and the solar wind. Methods originally developed for the Sun, such as for example magnetic field extrapolation, are now applied to other stars. Apart from other stars, many of the fundamental astrophysical processes we are able to observe in high spatial and temporal resolution on the Sun occur in other, more exotic, astrophysical plasmas. The Sun is provides a unique laboratory for understanding fundamental physical processes such as magnetic field generation and evolution, particle acceleration, magnetic instabilities, magnetic reconnection, plasma heating, plasma waves, magnetic turbulence and many more. The Sun, together with other solar system plasmas, can therefore be regarded as the Rosetta stone of astro-plasma physics.

The existence of life on Earth depends on the Sun, and its output and activity define the space environment in which we live - we effectively live in the Sun's outer atmosphere (the so-called Heliosphere). The influence of the Sun on our direct space environment can impact, for example, on satellite and communication technology and therefore is important for the functioning of our modern technological society. Another aspect of the Sun's impact on our lives is the as yet unclear influence of the Sun on changes in the Earth's climate.

Solving these problems requires a large coordinated effort in connecting together many different strands such as multi-wavelength observations, theory and high performance computing. The UK holds a leading position within the international solar physics community in instrumentation, observational analysis, MHD theory and plasma physics with the participation of UK solar physicists being actively sought in major new projects. The UK has for the last 30 years held PI roles on the majority of the major international collaborative solar space missions, as well as the unique and highly regarded ground-based BiSON helioseismology network. Thus, we are well placed for maintaining a leading and productive role in this field over the coming years, with a strategic approach to mission and facility involvement, analysis techniques and theory and modelling.

## Major Scientific Challenges

Solar physics faces major scientific challenges due to the extraordinary and surprising complexity of the physical processes we have discovered on the Sun over the past couple of decades. Ultimately, these phenomena are driven by the flow of energy, generated in the Sun's core, through its interior and its atmosphere, into interplanetary space. The energy is carried by the solar magnetic field and hence the key questions in solar physics focus on the understanding of the generation, emergence and dynamical behaviour of the Sun's magnetic field:

(1) What is the nature of flows in the solar interior and of the solar dynamo generating the solar magnetic field?
(2) How do magnetic fields emerge into the solar atmosphere?
(3) How do magnetic fields develop into the complex dynamic structure in the solar atmosphere including all aspects of solar activity from small-scale structures and wave activity to flares and coronal mass ejections?
(4) How does the release of coronal energy lead to the structured, multi-thermal nature corona that is observed, as well as to the large number of energetic particles found in flares? How is the solar wind generated?
(5) How does solar activity affect the near Earth space environment as well as that of other planets, and how does the Sun influence our climate?

The Sun displays dynamical phenomena on length scales ranging from over one solar radius down to below the current spatial resolution limit. For example, even with a resolution of about 100 km, elementary magnetic flux tubes on the solar surface have still not been resolved. This vast range of spatial scales, coupled with an equally large range of time scales (ranging from decades to sub-seconds) and the intrinsically three-dimensional, non-linear aspect of solar phenomena provides theory and modelling with an enormous challenge. Addressing this cross-coupling between dynamical phenomena occurring on large scales and the underlying physical processes, involving scales we cannot yet resolve, will require us to overhaul our current theoretical models, to develop innovative approaches to theory and modelling and to fully exploit HPC facilities.

The fundamental questions listed above drive solar physics research. Our ever advancing observational capabilities and ever advancing modelling capabilities now finally overlap. This has meant that models have much more predictive power and can now be tested to a much greater extent than a few years ago. Not surprisingly, this extensive testing has revealed some significant short falls in our understanding at levels that cannot be tested anywhere else in the Universe. This means we can now formulate much more specified problems associated with each of the above question than it would have been possible before.

(1) The origin of both large scale and small-scale magnetic fields in the Sun is now believed to be dynamo action. Modelling the origin of solar magnetic activity involves understanding the interaction of magnetic fields with rotation, convection, shear flows and stable stratification and the structure and development of the solar tachocline and differential rotation. This theoretical underpinning is constrained by our knowledge of the solar interior through helioseismologyThe detection of internal oscillation modes that penetrate to given depths inside the Sun scales with the duration of the dataset, i.e. the longer the data set, the deeper the detected modes can reach. Moreover, the longer the duration of the data set the more significant the results become. Since there is no other way of probing the interior of the Sun, in particular, the base of the radiative zone or core, the extension of the longstanding ground based helioseismology experiments guarantees us new results that are certain to extend our understanding of the Sun's interior. In particular, the current experiments have been going for long enough for us now to begin to measure the first gravity modes – i.e. to measure oscillations that penetrate the core and thus provide us information of the density and temperature near to the centre of the Sun.

(2) Magnetic fields emerge on all spatial scales, ranging from active regions to small ephemeral regions and even smaller. What does this tells us about the form of the field in the solar interior? Is buoyancy or convection the most important physical process involved? Is there a small-scale dynamo operating just below the photosopheric surface? How do sunspots form and evolve? Is the magnetic carpet responsible for heating the quiet Sun? We need to improve our fundamental understanding of how the magnetic field in the interior couples to the solar atmosphere and how the emerged magnetic fields are processed in the photosphere once they have emerged.

(3) The magnetic fields that thread the solar surface fill and structure the solar atmosphere. This interaction of the plasma and magnetic field produces a number of dynamic phenomena whose size and lifetime evolve over a wide range of length and time scales. Many of these phenomena such as Coronal Mass Ejections, Solar Flares and Open Flux may directly affect the Earth. Understanding and eventually predicting these phenomena is of great importance. Key theoretical questions include: What role do small and large scale flows at the level of the photosphere play in the build up of energy and the reorganisation of atmospheric magnetic fields into complex energy releasing structures? How do these processes produce long term variations in solar activity? What mechanisms result in the release (tranfer) of energy both over small (few metres) and large (solar radii) length scales leading to solar flares and CMEs? How do CMEs propagate into the heliosphere? How do small and large-scale flows transport the Open Flux across the solar surface? What causes the variations in the level of open flux over short (days-weeks) and long (solar cycle) time scales? A key element in understanding these phenomena is the direct incorporation of observational data into theoretical models to first reproduce and understand these

complex systems and then to predict them.

(4) An underlying process involved in all solar phenomena is the transfer of magnetic energy into both thermal energy, kinetic energy and the acceleration of particles. Key questions relate to how, where, when and how much energy is transferred. What is the relative significance of the two main energy release mechanisms: reconnection and waves? What role does the complexity of the magnetic field play? What is the nature and implications of the coupling of MHD and kinetic scales for nanoflares/flares/eruptions? How is this energy transported and distributed in closed and open magnetic field regions? How is the plasma in open field regions accelerated producing the solar wind? What fraction of the energy stored in the corona goes into acceleration of the solar wind and into heating the corona?

(5) As a persistent material outflow from the Sun that carries with it the solar magnetic field, the solar wind and its interactions with bodies within the heliosphere can have a profound influence on their evolution. It is thus critical that both the origins at the Sun, and the evolution of the wind, are fully understood in order that we can understand the variations that we see *in situ*. In addition to the continuous outflow of the fast and slow solar wind, the Sun releases large-scale transients such as CMEs and SEP events that can have huge impacts on the near Earth environment. Key questions include: what is the global structure of the solar corona and the near Sun solar wind? What are the sources and acceleration mechanisms of the fast and slow solar wind? What are the drivers and effects of solar wind turbulence, and how and where are shocks accelerated? How are SEPs accelerated and transported?

(fast/slow), turbulence, CME and SEP impact, cosmic ray propagation, cloud formation etc

Understanding the truly complex nature of the solar magnetic field requires an investment in a wide range of solar and heliospheric observations at high resolution and at all latitudes coupled with data analysis and appropriate theory and modelling. The ultimate aim is to understand, on the one hand, the underlying basic physical processes such as magnetic reconnection, particle acceleration and wave generation and dissipation and, on the other hand, the physical links and impacts on the Earth's environment. The complex interactions and cross-scale coupling of the plasma in the solar atmosphere and heliosphere requires coordinated measurements of magnetic fields and detailed imaging and spectroscopy, combined with plasma diagnostic tools. So we can increase our overlap between observations and theory, but at the same time narrow the differences between them. To meet these challenges new instruments will need to be developed using innovative technology to go beyond the present limitations in terms of spatial and temporal resolution, in a range of wavelengths covering the entire solar atmosphere. To fully exploit the results of these new observations we will need to be equally inventive in our methods of data analysis and to develop radically improved numerical modelling and theoretical approaches.

## UK Areas of Excellence

The UK is internationally competitive in many areas, and especially in aspects of MHD and plasma theory, data analysis and instrumentation. As described above these areas are inter-linked.

1. Theory. The UK has several internationally recognized theory groups working on large scale simulations, mathematic modelling and atomic theory
    a. Developments in large-scale simulations, through the High Performance Computing facilities run by the UKMHD Consortium are essential to maintain our world leading research. HPC facilities are used in understanding all of the key questions in solar physics.
    b. The UK has led the way in understanding MHD wave theory in the solar atmosphere and the development of coronal seismology to use the observed wave motions to determine the local plasma properties.
    c. The UK has a long history in the detection and interpretation of global oscillations of the Sun. Helioseismology is a key tool in understanding the solar interior and recent developments has shown the existence of the tachocline at the base of the convection zone.
    d. The particle acceleration and transport problem is a key problem in solar flares. Several UK groups are internationally recognized experts in this area, as can be judged from the number of UK chapters in the forthcoming RHESSI volume.
    e. UK groups are internationally leading in the provision of atomic data for the interpretation of atomic spectra from spectrometers. CHIANTI is the preferred atomic physics package throughout the international solar community.
2. UK solar scientists have well established expertise in the use and analysis of many disparate datasets, with excellent track-records in the use of UK-led and non-UK-led instrumentation. Many novel techniques developed for this purpose are widely used internationally.
    a. Helioseismology data from the BISON network provides a unique long-term dataset that is critical to making the breakthrough in understanding the solar dynamo. The recent extended solar minimum emphasises the need to understand how the solar interior varies over more than one solar cycle. UK scientists also hold key science roles in the major existing international (SOHO, GONG, PICARD, Hinode) and forthcoming missions in helio and astroseismology (SDO, Solar Orbiter). We lead the international Solar FLAG efforts to search for g-modes.
    b. Spectroscopic observations of the solar atmosphere, combined with the essential atomic physics expertise to develop plasma diagnostic tools has been a key strength in the UK for many years, underpinning research into most solar atmospheric phenomenon. This is seen as one of the UK's great solar strengths. UK scientists have exploited spectroscopic and associated imaging data from missions such as SOHO, Hinode, STEREO, TRACE and RHESSI with great success and our spectroscopic strengths are highly sought after by the international community.

c. Emergence, evolution and eruption of magnetic fields and the tracking of the associated disturbances through the heliosphere to their impact at Earth. This includes the developing field of Heliospheric Imaging, in which the UK has played a leading role, with SMEI and STEREO; the UK STEREO HI instruments for the first time allow CMEs to be tracked from their solar origin to the Earth.

d. Solar wind and interplanetary scintillations. The UK involvement in Ulysses and Cluster, together with supporting theory, has produced much ground-breaking work in our understanding of the solar wind and its interactions within the heliosphere. Similarly expertise in the area of interplanetary scintillation has led to a key role for the UK in this area within the LOFAR consortium. New results from Hinode from within the UK are for the first time providing concrete evidence of the origins of the solar wind in the low corona.

3. Solar space instrumentation is principally concentrated at two main UK centres, with the emphasis on spectroscopic imaging of the outer solar atmosphere and heliospheric imaging. The RAL and MSSL groups have led major international consortia for instruments of this type over the past three decades (e.g. SMM, Yohkoh, SOHO, Hinode, STEREO) and have a world leading reputation in the associated science. In addition to these instrumental strengths the UK excels internationally in the provision of CCD and APS based camera systems and CCD detectors, and this is a key link to UK industry (e2v and Andor Technology). The recently commissioned ground-based ROSA instrument developed by QUB is being base-lined as one of the first generation instruments for the U.S. Advanced Technology Solar Telescope (ATST) and potentially for the European Solar Telescope (EST).

## Future Priorities and requirements

The UK solar community is extremely well placed to make significant and fundamental breakthroughs in the highest priority science questions in this area of the next 10-15 years, that is, understanding the origin and evolution of the solar magnetic field and its impacts on the Earth's environment. In order to achieve that goal we must maintain a critical mass within the community in terms of human resources and access to facilities that builds on our current strengths in theory, observation and instrumentation in the following areas (in no particular priority order):

1) Support and development of full 3-dimensional MHD and dynamo theory to provide a predictive framework for observations. This is crucial to enable us to fully exploit investment in any mission.

   ***Required resources:*** This primarily requires investment through the grants line in staff, PDRAs and access to high performance computing. Investment in this area supports a large fraction of the community and a medium to large investment over a long time-scale.

2) Essential strategy for solar observations: The underlying reasons for detailed studies of the solar interior, atmosphere and heliosphere are given above and are clearly high priority for a number of practical applications as well as for pure solar research interests. A strong observational programme, building on our established strengths and feeding our active research community is essential. The Sun is a highly complex system that we are in the fortunate position of being able to observe on scales that are approaching those of physical processes, but as a result of that complexity it is crucial to have access to observations that provide as complete a picture as possible and thus to have UK participation in relevant international projects. This must involve several elements, namely, a strong Post Launch Support and facility support programme, to maintain current observational resources, an active programme into new mission opportunities tuned to the UK's scientific interests and access to non-UK-led facilities. These are summarised below:

   a. Continuing Post Launch Support and facility support for existing involvements in SOHO, Hinode , STEREO, ROSA and BiSON. These provide and will continue to provide unique information on the solar interior (long-term well calibrated observations are crucial in this regard), on the solar atmosphere and heliosphere and, in particular, the link between the emergence and evolution of the solar magnetic field and the environment at Earth.

      ***Required resources:*** This requires a package of support for operations and exploitation. We need support for operations via the PLS line that provides funding for technical staff to maintain and operate instruments, scientific staff to support the community in the planning and execution of observations and resources to archive data and develop software. In parallel, we need appropriate support for exploitation through the grants line. Note that operations support forms an integral part of our obligations to international partners. Support for ROSA, BiSON, SOHO, Hinode and STEREO represent relatively small investments for high return.

   b. Solar Orbiter is the next major international solar mission. It is a partnership between ESA and NASA and the basic concept is for a solar multiple encounter and high latitude mission. This mission was jointly proposed to the ESA committees by Germany and the UK in 2000 and is well tuned to the development of the scientific strengths of both the solar and solar-terrestrial communities. Orbiter provides the next logical step observationally in providing the observations of the magnetic field at the poles that are a vital input to dynamo models. Its proximity to the Sun will also be crucial for identifying the origins and drivers of the solar wind and marrying remote sensing observations to in situ measurements of the solar wind plasma. The UK solar and solar terrestrial community already holds significant leadership (science or hardware) roles in four of the instruments on Solar Orbiter, and there is substantial UK technical expertise in the detector technology and thermal engineering required for the mission.

***Required resources:*** construction and operational support (large initial investment) plus support for exploitation through the grants line.

c. Access to data from RHESSI, ROSA, SDO and Nobeyama. RHESSI and Nobeyama provide unique information on particle acceleration and transport that is critical to understanding the processes involved in the eruptive events that affect our environment. ROSA provides unprecedented high-resolution images and spectral information about the most controversial part of the solar atmosphere: from photosphere to the top of the chromosphere allowing us to understand the coupling processes. SDO will provide vital heliosesimic, magnetic field and imaging data that provides constraints to dynamo and MHD models and allows the origins of eruptive phenomena to be identified.

***Required resources:*** exploitation through the grants line, access to high performance computing and facilities that enable the community to store, visualize and analyze large volumes of data. Resources to exploit the 20-day guaranteed observing time at DST with ROSA. Note that these are particular examples of high science return for relatively small financial investment.

d. Involvement in new opportunities. To maintain the strength and competitiveness of the community and the return on the UK investment we must build on existing scientific and technical strengths by participating in new projects. Future opportunities include the Chinese KuaFu mission, HiRISE mission, PROBA-3, the Advanced Technology Solar Telescope, JAXA's Solar C mission, the European Solar Telescope and LoFAR. All have science goals and capabilities directly aligned with the goals of the community, hardware opportunities that build on existing strengths and current UK involvement in science and/or hardware definition. Opportunities in KuaFu and Solar C would build directly on heritage from involvements in Hinode and the MOSES rocket programme, while those in ATST and EST would capitalize on UK strengths in detector and camera technologies, and recent investment in ROSA. It is noteworthy that following its involvement in the provision of cameras for ROSA Andor Technology has seen a significant increase of sales of similar cameras to the wider scientific community, and a recent 40% increase in turnover. HiRISE, with its unprecedented high time and spatial resolution in EUV, though high-risk in concept, would bring solar physics to completely uncharted territories, as would the high resolution coronagraph observations of PROBA-3.

   ***Required resources:*** support for studies and proposals, construction, operation and exploitation (in some cases).

## Broader benefits to the UK

The Treasury definition of Economic Impact includes reference to the environment. Our local environment is defined by and subject to the outputs and variations from the Sun. Thus, our research into solar processes and impacts at Earth are of direct relevance to this issue. We must also note that this is an area of growing economic interest. Thus, our solar research programme is already well suited to addressing key environmental issues and continues to develop in this direction with the proposed mission and facility involvements and associated analysis and modelling projects.

In parallel, there is a strong link to UK industry. Solar instrumentation requirements are demanding – detectors require high spatial and temporal resolution and large formats, making them appealing for much wider markets, as demonstrated by the increase in turnover seen by Andor and by the track record of e2v. Future instruments will require further detector development and large data volumes require intelligent processing techniques that could find applications in defence, climate and Earth monitoring. Involvement in international space projects provides a direct benefit to the UK economy. For example RAL and e2v have provided many camera systems to international partners through direct contracts.

Parallel technology developments in optical systems, space instrument mechanisms, thermal engineering etc… all benefit from the involvement in solar missions.

Solar theory and particularly computational MHD, provides training not only in logical thought, but also in high performance computing skills that are required in finance, industry and government.

To finish, expending on the point made above regarding the local space environment, a recent NASA funded U.S. report emphasizes that the potential impacts of a large geomagnetic storm on our society can be huge [http://www.nap.edu/catalog/12507.html]. In a technological age we rely completely on infrastructure to provide basic services such as power and water that are vulnerable to such an event. While we cannot prevent such an event, developing more reliable predictors of solar activity can help us to mitigate potential effects. And while anthropogenic forcing is clearly the most pressing issue in climate change currently, we cannot escape the fact that variations in the solar output and their impacts on climate are poorly understood. The recent deviation of the Sun's behaviour from previous cycles and our lack for understanding of the reasons for this highlights the requirement for better understanding of what controls solar irradiance variations. We need to understand our local star.