Community paper
„The Sun: a laboratory for stellar and plasma physics“

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Executive summary

Over the last decade solar and heliospheric research in Germany moved the field significantly forward through an interlocked combination of new observing facilities, advanced data analysis methods, and a leading role in numerical modeling. Therefore German research is in a very strong position to address the key questions for the coming decade:

- How do solar and stellar activity, in particular the magnetic field generating dynamo, work?
- How does a cool star drive and sustain its hot outer atmosphere?
- How does the Sun connect to the heliosphere?
- How does the Sun affect Earth's climate and which are the governing processes on the Sun?
- How does the Sun relate to other stars with their planetary systems?
- How does the Sun drive Space Weather that impacts our technology-based civilisation?

To keep a leading role in solar physics and to be able to adequately address the above key problems, the German community needs access to international infrastructure projects of the next generation:

- A large-aperture high-resolution solar facility,
- a space-based high throughput extreme ultraviolet imaging spectrometer, and
- a new facility for synoptic continuous observations of the Sun.

German research institutions have played a key part in defining these future facilities and are capable and willing to take a leading role in these endeavours, given the availability of adequate funding. These facilities would ensure the continuing success of German research in our understanding of the Sun, how it relates to other stars and how it influences the heliosphere as well as the Earth.

1. Introduction

The Sun is the only star where we can resolve the structure and dynamics in its atmosphere, on its surface, but also in its interior at many of the scales relevant for the central physical processes. The proximity of our own star makes it a fundamental stepping stone for stellar astrophysics. The physics of the Sun is interlinked with many other fields:

- *Stellar Physics*: Understanding the internal structure, dynamos, activity, and winds of other stars is closely linked to the Sun. Here we see the individual multi-scale structures from well below 100 km to the solar diameter of more than 10^6 km that make up the single spectrum of most other, unresolved stars.
- *Exoplanets*: Earth is the only planet known to host life. To investigate how stars shape their habitable zones and improve several planet detection techniques, observations of the Sun play a key role.
- *Cosmic astrophysics*: While cosmic magnetic fields are often governed by boundary conditions quite different from the Sun, the languages of magnetohydrodynamics and plasma physics are the same and are advanced by and tested on processes on our own star.
- *Plasma physics*: Plasma parameters in lab experiments and fusion share the same ranges as the outer solar atmosphere and the heliosphere. This shows synergies to understand particle acceleration, turbulence, and other basic physics processes.
- *Earth sciences*: Eruptive events on the Sun and the variation of the solar irradiance have significant impact on Earth, ranging from threats to our technology-based civilisation to climate change.

This close link to other fields of science but also the beauty of the physics of processes in and on the Sun itself makes our own star an object of highest interest in contemporary astrophysics.

2. Key Questions for the Upcoming Decade

2.1 Understanding solar and stellar activity: the dynamo

One of the major enigmas in astrophysics is the generation of the magnetic field in a global dynamo process. In the case of our own star, this controls the 11-year activity cycle. The variation we observe in the solar atmosphere through the presence of, e.g., sunspots or flares is only the tip of the magnetic field produced by the global dynamo operating in the convection zone where it converts kinetic energy of convective motions into magnetic energy. In the standard dynamo model the poloidal magnetic field from pole to pole is wound up primarily by latitudinal differential rotation to produce toroidal magnetic field. Once the latter is strong enough it erupts through the surface where it forms sunspot groups. Their tilt with respect to the equator converts the toroidal field back to poloidal field, conceptually completing the cycle.

A major challenge for the coming decade will be understanding both processes most relevant for the dynamo, i.e. flows in the solar interior (e.g., differential rotation, meridional circulation, etc.) and emergence of magnetic flux. The former are most poorly known at high latitudes. Future observations out of the ecliptic by Solar Orbiter (Sect. 2.3) will have a clear view of the poles and will close this gap, but next-generation synoptic observations will be needed to get better access to the interior flows (Sect. 5.3). The second key process, emergence and formation of sunspots, will be greatly advanced by high-resolution observations with a future large-aperture solar telescope (Sect. 5.1) in combination with state-of-the-art simulations. Understanding the response of the upper atmosphere to these small-scale processes requires a next generation extreme ultraviolet spectrometer (Sect. 5.2).

Another key question concerns the spatial scales of convection in the solar interior, and how these drive the differential rotation, which powers the global dynamo. There is currently a disagreement of several orders of magnitude between simulations and the helioseismic analysis of observations concerning the strength of the convection at large spatial scales. One proposal to resolve this invokes a small-scale dynamo (Sect. 3.3), whose observational confirmation has so far remained elusive and which will finally be constrained by a next-generation high-resolution solar telescope (Sect. 5.1).

Understanding how the magnetic fields are generated in the solar interior, and how they are influenced by convection and emerge through the surface is critical to a full understanding of solar activity and the structure of the solar atmosphere, including magnetic and thermodynamic aspects.

2.2 How does a cool star sustain its hot outer atmosphere?

The surfaces of the Sun and other cool stars are surrounded by hot outer atmospheres. Above the visible surface, the photosphere, the averaged temperature gently rises in the chromosphere before it steeply climbs to more than a million Kelvin in the so-called transition region to the corona. In both the chromosphere and the corona the magnetic field plays a pivotal role in defining the atmospheric structure and dynamics. Most importantly, the magnetic field is the main agent channeling the energy flow and also heating the plasma through dissipation of magnetic field, e.g. through reconnection.

The challenging task in this domain of the Sun is to get a holistic picture of the transport of the energy from the surface convective motions into the upper atmosphere, the exchange of mass between the chromosphere and the corona and the actual dissipation of magnetic energy and its conversion into kinetic energy, i.e. mass motions and particle acceleration, and thermal energy, i.e. heating. The complex non-equilibrium radiative processes required to describe the chromosphere and the complex interaction of plasma and magnetic field throughout the upper atmospheres make this endeavor particularly challenging. One relevant problem is the inclusion of microscopic processes, e.g. the energy dissipation, into the macroscopic description of the phenomena on observable scales. This multi-scale coupling (Sect. 3.4) is a major challenge for modeling and for constraining modeling results by observations. In-situ measurements in the inner heliosphere can provide key information on the role of turbulence and reconnection in these processes.

For further progress a new generation of solar observing facilities is required. These should allow investigating the upper atmosphere from 10^4 K to 10^7 K through extreme UV imaging spectroscopy (Sect. 5.2) and measuring the magnetic field in the solar atmosphere with unprecedented accuracy (Sect. 5.1). Together with the expected advancements in realistic numerical simulations of the solar atmosphere, this will pave the road for a better understanding of the processes that control the radiative output of the Sun and its impact on Earth (Sect. 2.4).

2.3 How does the Sun connect to the heliosphere?

The outer atmosphere of the Sun expands into interplanetary space and fills the heliosphere with turbulent plasma and magnetic field. The acceleration of the plasma forming the solar wind and the heating of the corona has to be treated as one coupled problem. As such, it is pivotal that we understand the magnetic connectivity and the initial acceleration of the ejected particles, which we refer to as the connection from the Sun to the heliosphere. Only then can we hope to fully grasp the processes governing the impact of our central star on Earth in terms of Space Weather (Sect. 2.6).

The basic question on how the Sun connects to the heliosphere will be addressed by Solar Orbiter, ESA's M1 mission to be launched in 2018. This platform will carry remote-sensing instruments to investigate the solar atmosphere as well as an in-situ package to measure solar wind properties, energetic particles, waves and fields (Sect. 4.1). Together with the unique orbit bringing it as close as 0.28 astronomical units to the Sun (inside Mercury's orbit) and to high heliographic latitudes (above 30°) this will be ideal to study the Sun-heliosphere connection. Solar Orbiter will capture solar wind and energetic particles before mixing processes dilute their signatures by exploring the uncharted innermost region of the solar system. The close proximity to the Sun will allow probing our central star and the heliosphere from a nearly co-rotating vantage point, disentangling spatial and temporal variations to gain new insights into evolution effects. Seeing the Sun with different instruments from the same vantage point is prerequisite to understanding the magnetic coupling from Sun to the inner heliosphere.

Solar Orbiter will provide fundamental new insights into the connection from the Sun to the heliosphere. At the same time through Solar Orbiter we will probe the workings of the solar (and thus stellar) dynamo (Sect. 2.1) by the first reliable imaging of the interior and surface layers of the Sun's polar regions.

2.4 Solar impact on Earth's climate

While the Sun's particle radiation and magnetic field govern the changes in the Earth's magnetosphere (Sect. 2.6), for Earth's climate the main driver is the solar total and spectral irradiance. The most pressing needs for the next decade are to gain an understanding of the variability of the spectral irradiance over the solar cycle and the magnitude of the secular trend.

Probably most important for climate is solar ultraviolet radiation that is almost entirely absorbed in the Earth's atmosphere and thus influences its energy balance and chemistry. The solar variability is considerably stronger in the ultraviolet than in the visible and infrared and is governed by changes in small-scale magnetic features on the Sun, i.e. magnetic flux tubes at the resolution limit of the best current solar telescopes. To investigate the overall spectral irradiance variation we have to study these small-scale features on the Sun, requiring a next-generation high-resolution solar telescope (Sect. 5.1)

To understand the solar irradiance change over centuries, again such small-scale features are of great relevance. Whereas strong magnetic features are responsible for irradiance variations on the rotational and 11-year activity cycle timescales, changes in the coverage by very small-scale magnetic elements (the network) are believed to cause the secular variation in irradiance. Once more, there is a coupling from the smallest scales to the Sun as a whole. High magnetic sensitivity is a prerequisite to study the relevant small-scale weak magnetic features, requiring a large-aperture solar telescope (Sect. 5.1) to achieve the necessary signal-to-noise ratio and magnetic sensitivity.

The study of the smallest and weakest magnetic features on the Sun is therefore key to understanding the solar irradiance changes and, thus, the impact of our own star on climate, life and habitability on Earth, and then, in turn, the impact of other host stars on their planets.

2.5 Solar-stellar connection

The Sun shows that multi-scale coupling is a key to understanding the physics, e.g. underlying the radiation spectrum, of our host star. On the Sun we see which structures contribute how much on which spatial and temporal scales, so naturally the Sun is a primary reference to investigate other stars. The major questions in solar-stellar research concern the understanding of the activity of stars: How does the operation of the dynamo create different activity cycles? What determines the appearance of magnetic structures (e.g. huge polar starspots vs. small sunspots) on the surface? How does the upper atmosphere at the X-ray radiation originating from there couple to the surface magnetic fields? One element to answer such questions is are high-quality Sun-as-a-star spectra, as they will be provided, for example, by the Solar Disk-Integrated (SDI) telescope feeding the PEPSI spectrograph at LBT

Understanding the formation, diversity, and habitability of exoplanets is a major goal for astrophysics in the upcoming decade. This requires the characterization of a statistically significant sample of exoplanets, including planets in the habitable zones of their wind-driving host stars. ESA's PLATO mission, to be launched in 2024, is the next-generation planetary transit experiment. Its main objective is to discover and characterize Earth-like exoplanets around Sun-like stars, over a large fraction of the sky. While it builds on the heritage from CoRoT and Kepler, the major breakthrough to be achieved by PLATO will come from observing tens of thousands of bright stars like the Sun, bright enough for high-precision asteroseismology and follow-up ground-based spectroscopy. The seismically-determined radii, masses, and ages of planet-host stars will be used to determine the radii, masses, and ages of the exoplanets to unprecedented precision. PLATO will identify a number of Earth-like exoplanets that will be ideal targets for future programs aiming at performing detailed analysis of planet atmosphere and searches for biomarkers.

2.6 The Sun as a particle accelerator and driver of Space Weather

The location of the habitable zone around a star depends on many factors, and even being within this zone does not save the Earth from energetic particles and disturbances of the interplanetary magnetic field originating from eruptive events on the Sun. This Space Weather has direct influence on our technology-based civilization in terms of damaging sensitive and expensive equipment in space and on ground. Understanding the physical basis of Space Weather will be one of the major challenges in the coming decade.

During eruptive events such as flares or coronal mass ejections (CMEs), a large number of energetic particles (electrons, protons, and heavy ions) are generated. These solar energetic particles can be accelerated either by magnetic reconnection and/or shocks in the corona or associated with coronal mass ejections in interplanetary space. Thus, the Sun is a giant particle accelerator. Energetic electrons play a key role because they are responsible for the non-thermal radio, hard X- and gamma-ray radiation. Furthermore they carry a substantial part of the energy released during a flare. The corona and inner heliosphere are ideal places for studying the mechanisms for generating energetic particles. Hence, investigating solar energetic particles and their acceleration is important not only for solar physics but for astrophysics and particle physics in general. A key facility for investigation of the dynamic coronal events at the Sun is a next-generation extreme ultraviolet spectrometer (Sect. 5.2) together with a synoptic facility allowing to the role of the interaction of interior flows with magnetic fields (Sect. 5.3).

The question on the largest possible flare and coronal mass ejection is of high interest not only form a pure physics point of view, but in particular also concerning its role for the Earth. In 1859 Carrington observed a flare that would cause significant damage to our high-tech infrastructure if it would happen today. In 2012 a similarly strong super-CME occurred, but luckily it missed the Earth. This and the observations of superflares on solar-like stars by Kepler motivates new investigations on the occurrence rate of such extreme events and their possible role on our civilization and on Space Weather in general.

To understand the relevant particle acceleration and transport mechanisms is one of the scientific goals of ESA's upcoming Solar Orbiter mission (Sect. 2.3). In concert with advanced modeling of the coupled system from the Sun to the Earth, the data from Solar Orbiter on its unique orbit in the inner heliosphere will be the key to getting a complete picture of the local environment and the Space Weather around our own star. However, due to its evolving orbit, Solar Orbiter will only provide snapshots from a given vantage point. A mission with high quality instruments permanently located away from the Sun-Earth line, e.g. at the Lagrange point L5, would greatly enhance our knowledge of the causes of Space Weather and of the propagation of CMEs towards Earth.

3. Key Results of the Previous Decade

The basis for the success of solar and heliospheric physics in Germany is the intimate interplay of high-quality observations and advanced numerical modeling. The high impact of this research, briefly summarized in the following, is made possible by the coordinated advancement of new observing facilities, data reduction techniques, and modeling (Sect. 4).

3.1 Helioseismology: peering into the Sun

Helioseismology has advanced our knowledge about the Sun's interior through observations of acoustic waves on the solar surface. With the launch of NASA's Solar Dynamics Observatory (Sect. 4.1) in 2010, the available high-resolution Doppler and magnetic field data have facilitated new discoveries.

Recent assessments of the large- and small-scale dynamics in the convection zone suggest smaller amplitudes for convective flows than reported from theoretical models. This raises fundamental questions how a star maintains its heat transport and redistributes its angular momentum that leads, e.g., to the observed differential rotation. The solar interior exhibits two shear layers, one near the surface and another one at the bottom of the convection zone. The solar dynamo could thus operate at these locations. Measurements of the meridional flow reveal its extent over the whole convection zone with a possible multi-cellular structure in latitude and depth. Determining precisely the amplitudes of the convective flows and the structure and temporal evolution of the meridional flow will be one of the research foci of the coming years.

Mapping the sub-surface structure and evolution of active regions is a challenging effort, too, since acoustic waves passing through them experience strong modifications. This results in ambiguities in the various helioseismic interpretations of flows and structures within sunspots and their surroundings. New constraints that could be incorporated into helioseismic analyses may come from the wave field measured in multiple heights of the atmosphere.

3.2 Solar surface magnetism

Improvements in instrumentation and in numerical modeling allowed significant progress in our understanding of the magnetism on the solar surface. High spatial resolution combined with excellent magnetic sensitivity achieved with the balloon-borne observatory Sunrise and now with the ground-based facility GREGOR (Sect. 4.1) allowed resolving fundamental magnetic features in the photosphere. For the first time kilo-Gauss flux tubes with diameters of only about 100 km and a space-filling magnetic field have been observed. They play a fundamental role in modulating solar irradiance (Sect. 3.5) and are the likely channels of the energy flux heating the upper atmosphere (Sect. 3.4). Models now reproduce many properties of not only these small flux tubes, but also of large sunspots. The radially structured penumbra of a spot is created by a magneto-convective process and small bright structures seen in the dark core of the spot, so-called umbral dots, are now understood as small convection pockets in regions of slightly reduced magnetic field within the umbra. When sunspots form, the emerging magnetic field reconnects in the photosphere in U-shaped loops. This is essential to remove the mass carried up from the interior that would otherwise prevent the magnetic field from emerging and is key to understanding how magnetic field fills the corona.

The mapping of magnetic features on other stars through Zeeman-Doppler imaging shows large-scale magnetic surface features, e.g. huge starspots near the poles, that are significantly different from the Sun. Although models can well-reproduce the locations of these spots, the physics-based modelling of their detailed structure and evolution is a challenge for the next decade (Sect. 2.5) and multi-scale considerations from the solar case will play a key role in this.

3.3 The small-scale dynamo under solar conditions

The kilo-Gauss features on the solar surface discussed in Sect. 3.2 exist in a ubiquitous weaker field. A magnetic field strength of 100 G is inferred from an interpretation of the Hanle effect to account for the observed lack of polarization in scattered light in Hanle-sensitive spectral lines. This weaker field is structured on scales below that which can be resolved with current telescopes. This magnetic field is thought to be the result of dynamo action driven directly by the turbulent convective flows.

Hidden beneath the solar surface these small-scale magnetic fields are likely to play a critical role in modifying the convective power spectrum and probably also in the maintenance of the Sun's differential rotation and meridional flows. Since these are the flows that drive the global dynamo (Sect. 2.1), the small-scale dynamo needs to be well understood before we can claim to have understood the global dynamo.

A substantial achievement in the last 10 years has been the study of these dynamo conditions in numerical simulations including the physical processes important in the convection zone and photosphere: compressible non-gray radiative magnetohydrodynamics with an equation of state including the effects of partial ionization. These simulations produce results that are directly comparable to observations, and the simulations of small-scale dynamo action show an impressive agreement with high-resolution observations (Sect. 4.1). The simulations however reveal that considerable and important action is taking place at scales below those that can be currently observed, which adds to the urgent need for a large-aperture ground-based solar facility (Sect. 5.1).

3.4 The corona: heated and driven by magnetic fields

The changing magnetic field on the surface governs the structure, dynamics, and heating of the upper atmosphere. The direct response of the upper atmosphere to this driving makes the upper atmosphere an ideal laboratory for the buildup, transport, and release of magnetic energy. During the most energetic reconnection events, in flares, the Sun's hard X-ray emission indicates that huge numbers of electrons are accelerated to high relativistic energies (over 30 keV) of more that one third of the speed of light. Detailed models of the plasma kinetics during magnetic reconnection prove that reconnection sites are an efficient source for energetic electrons. These models also highlighted the role of small-scale turbulence for fast reconnection and the formation of magnetic islands. Future observations at unprecedented spectral and spatial resolution in the extreme ultraviolet will provide a crucial test for such fundamental models (Sect. 5.2).

Magnetohydrodynamic (MHD) models on active region scales provided an understanding of the onset of magnetic eruptions through increasing magnetic twist, in the end leading to coronal mass ejections that can induce geomagnetic storms (Sect. 2.6). Realistic MHD models of active regions including the synthesis of coronal emission showed how the various coronal structures form in response to the Poynting flux energizing the corona. This confirmed the role of braiding magnetic field lines to heat the upper atmosphere by employing a detailed comparison of synthesized data with real observations (Sects. 4.1, 4.3). Together with ultraviolet imaging and spectroscopy these models provide first clues on the complex mass and energy exchange between the chromosphere and the corona (Sect. 2.3) due to fast jets, helical motions, or island reconnection.

3.5 Solar radiative output and solar activity

While solar activity is most apparent in the corona, most of the solar irradiance originates from the lower solar atmosphere. Measurements from space since 1978 reveal a variation of the total solar irradiance of about 0.1% over the 11-year cycle, but also changes on all other observed timescales. To understand this variation and to be able to reconstruct past solar irradiance, physical models are required. One of these uses magnetic field maps to identify and quantify the coverage by dark sunspots, smaller-scale bright faculae, and the quiet Sun, and combines them with calculated intensity spectra of these structures. This model replicates 96% of the measured irradiance variation since 1978. Using sunspot number observations, reconstructions of the irradiance have been extended back to 1610. The success of this model is underlined by its recommendation by the Intergovernmental Panel on Climate Change (IPCC-5) report and the Model Intercomparison Project 6 (MIP6) of the World Climate Research Programme.

The variability of the Sun on longer time scales can be investigated by using cosmogenic isotope data, such as ^{10}Be from ice cores or ^{14}C from trees. The production rate of these isotopes can be used as a proxy for solar activity, because it depends on the shielding of cosmic rays by the large-scale solar magnetic field. Such studies covering the Holocene, i.e. the last 12000 years, showed that in the 2nd half of the 20th century, the Sun was at an unusually high level of activity. Today, we can measure cosmic rays and model their modulation and the generation of cosmogenic nuclei. Still, a simulation of the climate change over the last millennium using this reconstructed solar forcing suggests that the high activity of the Sun cannot explain the global temperature rise over the last decades. This type of solar research has a direct societal impact.

4. Particular Role/Strengths of Research Groups in Germany

4.1 Key role in new instrumentation

Over the last decade several key solar observing facilities became available that have been either led by German institutions or to which Germany provided a significant contribution. Foremost among these is the ground-based 1.5-meter solar telescope GREGOR on the Canary Islands, which is capable of stellar observations too. Led by a German consortium, it became fully available for the scientific community in 2015 and is now producing first results (Sect. 3.2). The German-led balloon-borne 1-meter telescope Sunrise is the largest of its kind and had two successful flights in 2009 and 2013, allowing for uninterrupted data partly circumnavigating the arctic circle producing many new key results. It already is the by far most successful balloon-borne solar mission ever world-wide (Sects. 3.2, 3.3). A third flight is highly desirable and planned for the 2020-2021 timeframe.

To study the Sun and its interaction with the heliosphere, Germany is providing major contributions to ESA's Solar Orbiter mission to be launched in 2018 (Sect. 2.3). German institutions are leading or participating in five of the six remote-sensing instruments on the spacecraft and in three of the five in-situ packages.

For the global studies of the solar surface and interior Germany contributed significantly to NASA's Solar Dynamics Observatory (SDO) through a German Data Center (Sects. 3.1, 3.5). For the upper atmosphere Germany also had a science-only contribution to NASA's Interface Region Imaging Spectrograph (IRIS; Sect. 3.4). Furthermore, Germany has a long-standing tradition in solar radio observations that has been greatly advanced by employing the Low Frequency Array (LOFAR) radio-interferometer and the Atacama Large Millimeter Array (ALMA) for solar observations.

The outstanding post-focus instrumentation made in Germany is documented by, e.g., the UV imager on Sunrise or the sensitive spectro-polarimeter to investigate the solar magnetic field operation on the Canaries. To keep this leading role, currently there are several post-focus instruments under development: the Visible Tunable Filter (VTF), a spectro-polarimeter based on the largest Fabry-Perot etalons built so far, for the US ground-based 4-meter solar telescope DKIST, the Fast Solar Polarimeter (FSP) which will finally overcome the negative effects of seeing conditions on magnetic field measurements, or the Microlens Hyperspectral Imager (MiHI), a novel integral field spectropolarimeter, to capture image and spectral information strictly simultaneously on a scale not attempted for solar physics before.

4.2 Leading role in data analysis

Modern solar observations provide huge amounts of complex data that need equally complex analysis methods. German scientists play a leading role in developing and advancing key techniques. Pioneering work has been done on the implementation of (multi-conjugate) adaptive optics for extended low-contrast objects. This was a prerequisite for modern ground-based high-resolution solar observations. It is closely related to image reconstruction techniques for optical observations like speckle techniques or Multi-Object Multi-Frames Blind Deconvolution (MOMFBD). Also, imaging through radio-interferometry with the Low Frequency Array (LOFAR) has been advanced. The spectro-polarimetric data acquired in the visible and the infrared require inversion procedures to reliably deduce the magnetic field in the solar photosphere and chromosphere, and in Germany widely used codes have been developed for this using the Zeeman and Hanle effects. These have recently taken a big step with the introduction of coupled inversions for imaging spectro-polarimetry. To investigate the interior of the Sun, groups in Germany have the lead in developing new methods for helioseismology, in particular in the field of local helioseismology that allows the internal structure of the Sun to be imaged.

4.3. Leadership in modeling from the interior to the outer atmosphere

In addition to the strong role in observations there has been a constant and very successful development over the last decade to foster numerical simulations to achieve realistic modeling of most aspects of solar research. These modeling efforts include the solar interior, the dynamo, magneto-convection of the near-surface layers, the upper atmosphere, the radiative output of the Sun, or detailed plasma processes. In all these areas German groups made ground-breaking contributions, partly by developing advanced new codes for 3D (radiation) magnetohydrodynamics, (gyro-)kinetic, or particle-in-cell simulations. These simulations achieved breakthroughs in the modeling of the (small-scale) dynamo (Sect. 3.3), the solar surface magnetism including sunspots (Sect. 3.2), or the heating and structure of the corona (Sect. 3.4), to name but a few.

In modern solar physics realistic modeling plays a key role in the interpretation of the increasingly complex observational data. The intimate connection between observations and modeling becomes more and more relevant not only in the analysis of the data, but also in the definition of new instrumentation. Therefore, it is of pivotal interest to maintain and advance the leading role of the German solar community in terms of modeling.

5. Key Infrastructures needed/relevant for Researchers in Germany

5.1 Large-aperture high-resolution solar facility

Germany is a world leader in magnetic field investigation at high spatial resolution and high magnetic sensitivity. A 4-meter-class European ground-based telescope would reflect Germany's and

Europe's leading role in solar physics and is necessary to compete with progress in other parts of the world. Only such a large-aperture visible-to-infrared telescope can provide the spatial resolution and the signal-to-noise ratio to ensure sufficient polarimetric accuracy for magnetic field studies as required by future observational challenges. Such a large European Solar Telescope (EST) is already anchored in the Astronet roadmap and is part of the European Strategy Forum on Research Infrastructures (ESFRI) infrastructure roadmap 2016 of the European Commission. It has been extensively studied through EU FP7 and Horizons 2020 grants and been demonstrated to have the technical readiness to build and operate EST on the Canary Islands. The further evolution of the recent 1.5 m telescope GREGOR and the German development of the Visible Tunable Filter for the upcoming US 4 m telescope (Sect. 4.1) play a crucial part in the preparation for EST.

With such a large-aperture solar telescope German researchers will be able to address fundamental open questions such as the (existence of a small-scale) dynamo and the process of magnetic flux emergence at the solar surface (Sect. 2.1), the magnetic coupling and driving throughout the atmosphere (Sect. 2.2), the relation of small-scale magnetic flux to solar variability (Sect. 2.4) and their relevance for climate change, or for the solar-stellar connection (Sect. 2.5).

Complementary to such a large-aperture ground-based telescope would be a 1-meter-class optical telescope in space, combined with other instruments to obtain a seamless coverage of the solar atmosphere. Through a participation in the envisioned international (JAXA/NASA/ESA) solar space observatory Solar-C, Germany would have direct access to such an instrument, providing the long-term stability that cannot be achieved from ground. As a precursor to such a space mission a third flight of the German-led 1-meter balloon telescope Sunrise would be highly desirable (Sect. 4.1). With new instrumentation this third flight will provide a crucial instrumentation testbed for a future large solar space telescope and at the same time provide high-quality science data under near-space conditions to address the fundamental questions on the lower solar atmosphere.

5.2 High-throughput extreme-UV imaging spectrometer

Over the last two decades Germany has been a leader in investigating the magnetized upper solar atmosphere. An extreme-UV imaging spectrometer with unprecedented spatial and spectral resolution building on German instrument heritage will answer fundamental questions on the upper solar atmosphere. Such an instrument has been studied extensively for an ESA M-class mission proposal and for a contribution to a Japanese solar space observatory (LEMUR; Large European Module for solar Ultraviolet Research).

The spectrometer would cover a wavelength range of about 17 nm to 130 nm to ensure a complete coverage of plasma temperatures found in the upper solar atmosphere, ranging from 10^4 to 10^7 K. The spectral resolution will be sufficient to measure small Doppler shifts down to one km/s and details in the emission line profiles to disentangle line-of-sight confusion. The high photon efficiency of the instrument will ensure the possibility of producing raster maps with a sufficient cadence to follow the fast evolution of solar structures in the upper atmosphere.

This imaging spectrometer will be a critical instrument to understand the physics of the dynamics, heating, structure, and magnetic connectivity from the cool chromosphere to the hot corona. In particular, it will provide crucial information on the upper atmosphere's response to small-scale surface processes and flux emergence (Sect. 2.1), on the transport and dissipation of energy in the upper atmosphere (Sect. 2.2), on the source of the connection of the Sun to the heliosphere (Sect. 2.3), or on the basis of the processes accelerating particles that ultimately can have an impact on the Earth's magnetosphere and ionosphere (Sect. 2.6).

Such a high-throughput extreme-UV imaging spectrometer could be either the main instrument on a standalone German or German-led space mission, or it could be part of a larger international space-based solar observatory, like the envisioned JAXA/NASA/ESA Solar-C mission.

5.3 Synoptic observations of the Sun as a whole

High-resolution telescopes such as GREGOR (Sect. 4.1) by design provide a field-of-view covering only a small fraction of the solar surface. Complementary real-time context data showing the large-scale dynamics and magnetism at different layers of the solar atmosphere are crucial to understand the global behavior of solar phenomena.

Therefore, synoptic observations are essential for unraveling the working of the global solar dynamo (Sect. 2.1) and answering how the Sun's magnetic field is generated, maintained and dissipated. They are the only possibility for addressing how the magnetic field influences the internal structure of the Sun and for comparing the Sun with other stars (Sect. 2.5). Furthermore they will help to decipher the processes in transient events by determining the role of the interaction of interior flows and magnetic fields (Sect. 2.6).

Despite the amount of information coming from space- and ground-based full-Sun telescopes, real-time information about the variation of important parameters such as velocities, magnetic field and intensity at different heights in the solar atmosphere is still lacking. One option to achieve this is a worldwide network of telescopes with small aperture but large field-of-view. The proposed SPRING (Solar Physics Research Integrated Network Group) network will provide improved magetometry and helioseismology for solar synoptic observations. It will be an invaluable resource for the long-term monitoring of solar surface magnetic fields and surface and sub-surface flow fields. As a side product it will provide context imaging for the next-generation high-resolution telescopes.

For studying the direct connection between the Earth and the Sun and Space Weather (Sect. 2.6), a new observatory at L5 is required. Only from that vantage point one can continuously monitor transient events on the Sun and their propagation towards the Earth. One step is this direction is the upcoming Earth-orbit-based coronagraph mission PROBA3 by ESA with German participation.

6. Summary and Conclusion

Investigating the Sun is an interesting and important quest, embedded in astrophysics and with close ties to other fields of science. Germany plays a leading role in most fields of solar research which is documented by key contributions to the structure of the Sun's interior, its magnetism and activity, and the resulting consequences for the heliosphere and on Earth. German research groups have a very strong position in developing new instrumentation, data analysis tools, and modeling frameworks. The close interaction between these three pillars is a central element of the solar research philosophy, and with the leading role in these fields German research is very well prepared to address the upcoming major questions.

The key problems for the next decade are: how does the Sun create its cycle of magnetic activity? What are the consequences of the solar magnetic field for the solar atmosphere from the surface to the hot corona? How does the solar magnetic field drive the heliosphere and create Space Weather? The resulting interaction of solar activity with the Earth's magnetosphere and in particular the magnitude and spectral form of the variation of solar radiation and its impact on Earth's climate is another key problem with great societal relevance that needs to be addressed. Finally, the Sun is a stepping stone to understanding other stars, and plays a critical role for understanding stellar variability and activity.

The upcoming challenges require next-generation solar observing facilities. These have to address scales from the whole Sun down to spatial scales well below what can currently be resolved, all with unprecedented polarimetric accuracy. For the high-resolution observations there is the need for a large-aperture ground-based telescope, the EST, to observe features in the photosphere and the chromosphere, and a high-throughput extreme-UV imaging spectrometer to observe the chromosphere and corona from space (LEMUR). For monitoring the Sun, a new ground-based network (SPRING) and a Space Weather observatory at L5 will be highly desirable. These next-generation facilities will ensure that Germany will be able to keep its leading role in understanding the inner workings of our own star, the Sun.