Cover picture: A decaying sunspot near the disk center observed with the Broad-Band Imager of GREGOR in May 2013 at a wavelength of 589 nm. This reconstructed image is based on 100 short (1 ms) exposures obtained with the GREGOR Adaptive Optics System. Image processing with KISIP.
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Summary

UNDERSTANDING THE SUN is the key to understanding the stars and the habitability of planets. Thanks to its close vicinity to Earth, the Sun is the only star that can be scrutinized in detail. On the Sun we see a wealth of structure and activity, far beyond of what can be studied in the laboratory. On the other hand, the Sun is our home star. It is a source of energy for life on the Earth, and its radiation and activity directly influences the conditions on our planet. While solar physics undergoes an unprecedented development, the following major issues remain unsolved:

- Origin, structure and evolution of the Sun’s magnetic field
- Hydrodynamic structure of the convection zone and operation of the dynamo
- Heating of the outer atmosphere
- Coupling between the Sun and Earth

The Kiepenheuer-Institut für Sonnenphysik conducts research on fundamental astrophysics, with a particular emphasis on the Sun, and focuses its activity on solving the major issues in solar physics. Research projects of the Kiepenheuer-Institut are organized into three main areas. The solar magnetism is the common thread through, and link between, these research foci.

RESEARCH FOCI

SUN: This focus aims at understanding the magneto-convective processes and structures on the Sun, both on the best possible detail delivered by observations and numerical simulations, and on global scales within the Sun and w.r.t. the coupling of the Sun-Earth system.

STARS: This research focus extends the horizon towards other stars and their planetary environments. These offer a means to study models for the solar magneto-convection under different physical conditions.

TECHNIQUES: This research focus aims at the development of high-sensitivity techniques and analysis methods for imaging, spectroscopy and polarimetry of solar surface structures, stars and exoplanets.

The institute operates the German solar telescopes on Tenerife, Spain, and provides a strong theoretical foundation for interpretation of data and modeling physical processes in the solar interior and up to the upper atmosphere. With the 1.5-m telescope GREGOR, in operation since 2012, the Kiepenheuer-Institut has one of the world’s most powerful solar telescopes.

The Kiepenheuer-Institut cooperates with German partner institutes, as well as with leading research institutions in the US, Europe, and elsewhere

RESEARCH TOOLS

Research in the Kiepenheuer-Institut relies on the cooperation between experimental and theoretical physicists, and on the expertise in the instrumental development.

Theoretical research and data analysis are supported by the computer facilities of the institute, including a net of workstations and PCs and a Linux cluster. External computing resources are being used as needed.

Instrument development at the Kiepenheuer-Institut focuses on ground-based telescopes. In addition, KIS participates in balloon and space projects. The main facilities and projects include:

- The 1.5-m telescope GREGOR, a technological challenge, with the first multi-conjugated adaptive-optics system. GREGOR provides observing conditions superior to all present solar telescopes. GREGOR is presently equipped with a broad-band imager, a Fabry-Pérot interferometer and an infrared spectro-polarimeter.
- The Vacuum Tower Telescope (VTT) on Tenerife with Echelle spectrograph, Fabry-Pérot interferometers, polarimeters, a laser frequency comb for absolute wavelength calibration, and an adaptive-optics system.
- The 10-cm telescope ChroTel, which portrays the chromosphere of the full Sun simultaneously in three spectral lines.
The European Solar Telescope (EST), the next-generation solar telescope in Europe, for which KIS leads several work packages in the design study.

The 4-m Advanced Technology Solar Telescope (ATST). The Kiepenheuer-Institut will contribute to this US project with the experience gained from GREGOR and will build the Visible Tunable Filter (VTF) as one of the first-light instruments for ATST.

The 1-m balloon-borne telescope SUNRISE. KIS contributed to this international cooperation the image stabilization and telescope alignment system.

The SOLAR ORBITER. This ESA-F2 mission will get closer to the Sun than all previous space probes. KIS will contribute to the image stabilization system.

The next-generation ground-based network for solar synoptic observations SPRING (Solar Physics Research Integrated Network Group), for which KIS leads the design study as part of its activities in the High-Resolution Solar Physics Network (SOLARNET).

EDUCATION and PUBLIC OUTREACH

KIS represents astrophysics in the curriculum of the Faculty for Mathematics and Physics of the Albert-Ludwigs-Universität Freiburg. Teaching includes lecturing, practical training at the Schauinsland Observatory, student seminars, and research trainee positions.

KIS conducts an undergraduate and graduate program at the institute that attracts a steady influx of young researchers funded through various third-party sources.

Public outreach activities include tours at the Schauinsland Observatory and at the VTT, information days for high school students, a teacher’s seminar, contacts with amateur astronomers, public lectures, press releases, and the World Wide Web.
Timeline of instrumental projects

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Legend:
- **design development**
- **construction commissioning**
- **science operation**
Research Capacities

The Kiepenheuer-Institut für Sonnenphysik (KIS) conducts experimental and theoretical research in astronomy and astrophysics, with particular emphasis on solar physics.

The long-term goal of the Kiepenheuer-Institut is to achieve a better understanding of the Sun as a unified physical system, including its variable influence on the planets and their space environment. To this aim, the institute will pursue an interdisciplinary approach to the phenomenon of the solar activity and its influence on the Earth. It focuses research on a number of selected topics deemed to play a key role for the understanding of the system Sun. It endeavors to contribute outstanding research results in these topics. While pursuing these goals, the institute supports a strong linkage of experimental and theoretical work.

The Kiepenheuer-Institut carries out an internationally recognized program in solar and space research. The most important partners of KIS include the Max-Planck Institute for Solar System Research (MPS, Germany), the Leibniz-Institut für Astrophysik Potsdam (AIP; Germany), the High Altitude Observatory (HAO, Boulder, USA), the Instituto de Astrofísica de Andalucía (IAA, Granada, Spain), the Instituto de Astrofísica de Canarias (IAC, Tenerife, Spain), the Lockheed-Martin Solar and Astrophysics Laboratory (LMSAL, Palo Alto, USA), the National Solar Observatory (NSO, Tucson, USA), the Istituto Ricerche Solari Locarno (IRSOL, Switzerland), and the Institute for Astronomy University of Hawaii (Ifa UH, USA). KIS endeavors to preserve and expand its international cooperation.

The Kiepenheuer-Institut currently coordinates the European Helio- and Asteroseismology Network (HELAS), which initiated the international project “Exploitation of Space data for Innovative Helio- and Asteroseismolgy (Spaceln)”. Furthermore, the Kiepenheuer-Institut has a leading role in the “High-Resolution Solar Physics Network (SOLARNET)”. Both projects are within the programs of the European Commission. Another important project is the “Centre for Advanced Solar Spectro-polarimetric Data Analysis (CASSDA)” to provide accurate spectroscopic and spectro-polarimetric data sets. This project is funded by the Leibniz Association (Pakt für Forschung). KIS hosts the executive office of the European Association for Solar Telescopes (EAST) and manages EC-funded access to the four European solar telescopes that participate in the SOLARNET program.

Two prestigious ERC (European Research Council) projects are currently implemented at the Kiepenheuer-Institut: the ERC Advanced Grant “Hot Molecules in Exoplanets and Inner Disks” (HotMol, PI: Svetlana Berdyugina) and the ERC Starting Grant “The Origin of Solar Activity” (ORIGIN, PI: Markus Roth).

The Kiepenheuer-Institut operates the German solar telescopes at the Observatorio del Teide, Tenerife, and the Instituto de Astrofísica de Canarias (IAC, Tenerife, Spain), Tenerefe, and coordinates the cooperation with German partner institutes (AIP and MPS). KIS implements the work required for the operation and the development of the post-focus instrumentation in its workshops in Freiburg. Additional post-focus instruments are provided by the partner institutes.

Recently, the Kiepenheuer-Institut, together with its partner institutes, commissioned the new 1.5-m telescope GREGOR. It features a number of innovative technologies including the first multi-conjugated adaptive-optics system. GREGOR should provide the worldwide best ground-based facility for experimental investigation in solar physics until completion of the 4-m Advanced Technology Solar Telescope in 2017.

In the theoretical work, numerical simulations and inversion methods play a increasingly important role. One aim is to simulate solar and astrophysical processes to a high degree of realism which can be directly compared with actual observations. Another goal is to develop efficient inversion methods for data analysis which can provide physical constraints for theoretical models. This interaction between theory and observations aims at understanding the variety of solar phenomena and their relation with each other, in terms of basic physical models.

In support of the theoretical and experimental work, KIS operates computer networks in Freiburg and Izaña, including a Linux cluster. For the numerical simulations additional computer capacity is obtained from the University of Freiburg and the High-Performance Computing Center Stuttgart (HLRS).
The main goal of this research focus is the advancement of our understanding of the solar magnetism, in particular the magnetic structure formation and the role of magnetic fields in the energy transport from the uppermost layers of the convection zone through the photosphere to the outer atmosphere of the Sun.

The solar photosphere allows most precise measurements of magnetic fields and detailed observations of magnetohydrodynamic processes on smallest scales. Also within and beneath the photosphere, the main mode of the energy transport changes from convective to radiative. There, the approximate equipartition between thermal, magnetic, and kinetic energy densities gives rise to a rich variety of process couplings. Further out in the chromosphere and in the outer atmosphere, the magnetic field energy dominates the thermal energy density, while the latter is increased by the dissipation of mechanical energy. The magnetic and non-magnetic coupling processes between the convection zone and the outer atmosphere make the photosphere a very special layer of the stellar structure worth to be scrutinized at highest possible spatial and temporal resolution.

Our research on the solar magnetism concentrates on the following topics:

- **SMALL-SCALE PHENOMENA**, with the emphasis on magnetic elements, faculae, and the turbulent magnetic field.
- **FUNDAMENTAL PROCESSES** on small scales, such as magnetoconvection, MHD turbulence, magnetic field intensification and dissipation, and energy transport.
- **SUNSPOTS**, with the goal to understand their stability, structure, dynamics, energetics, formation, and decay.
- **SUBSURFACE STRUCTURES AND FLOWS**, concentrating on the one hand on the helioseismic signatures of subsurface structures and flows, and on the other hand on the retrieval of meaningful physical parameters for these structures and their connection to surface features.
- **CHROMOSPHERIC HEATING AND DYNAMICS**, in particular the propagation, conversion, and dissipation of various magnetohydrodynamic waves in the solar atmosphere, and small-scale magnetic reconnection and associated formation of small-scale jet phenomena.
- **MAGNETIC FLUX EMERGENCE** and the formation of unstable magnetic configurations in view of forecasting large scale events like flares and CMEs.

**Small-scale phenomena**

The Sun is the only star of which we can study magnetic fields on small spatial scales. Our goal is to understand how small-scale magnetic flux concentrations form and the role they play in the energy transport from the convection zone to the solar atmosphere.

**Network elements**

Magnetic elements are small concentrations of magnetic flux in the photosphere. They are particularly well visible in certain molecular bands, where they show a high intensity contrast. As they are most abundant in plage and network regions they must play a distinctive role in the transport of mechanical energy to the outer layers of the atmosphere, which show enhanced emission in these locations.

Recent numerical simulations suggest that magnetic elements possess substructure in the form of tiny sheets and knots of diverse magnetic polarities and that vortical motion at their footpoints has a crucial impact on the chromosphere.

By means of simultaneous high-resolution spectropolarimetric observations in multiple wavelength regions, with the best available solar telescopes, we want to find out more about this substructure and about vortical motions. Observations are to be complemented with multi-dimensional time-dependent numerical simulations ab initio from the equations of magnetohydrodynamics and radiative transfer. Thus, the interaction of convection, radiation, and magnetic field in the layers of the solar atmosphere close to the surface shall be investigated. Diagnostic quantities, such as the profiles of spectral lines in polarized light, will be observed and compared with corresponding quantities synthesized from the simulations.

**Faculae**

Towards the solar limb, magnetic elements grow in brightness and turn into faculae—besides sunspots, the most prominent feature of the white light solar disk. Faculae are responsible for the pro-cyclical variability in solar irradiance. To date the precise location,
orientation, strength, and dynamics of the magnetic field associated with faculae is poorly known. An important unanswered question is why small magnetic flux concentrations radiate above-average amounts of energy into space, how much exactly, in which direction and depending on which physical parameters? We plan to answer these questions with the help of ground-based and space-based observations. In combination with numerical simulations we seek to establish a unified model of faculae, which should quantify their excess energy loss as a function of a few parameters such as size and field strength.

While for the Sun we know that faculae cause a pro-cyclic variability of solar radiation, this need not to be the case for other stellar atmospheres. We plan to investigate under which conditions faculae can form in stellar atmospheres. For example, first comparative magnetoconvective simulations for a solar and a solar analogus atmosphere of reduced metallicity that we have carried out show much stronger horizontal fields in the metal-poor atmosphere. Such comparative studies are expected to shed new light on the physical nature of the small-scale magnetic field and its effect on radiation in stellar atmospheres and on the Sun.

**Turbulent magnetic fields**

On even smaller scales, the solar magnetic field is ubiquitous and highly entangled. This field is believed to be generated by a turbulent dynamo acting in the turbulent subsurface layers: it may sustain a significant part of the magnetic energy at the solar surface. Observations of the turbulent magnetic field, however, have remained unresolved so far because of the polarimetric cancellation in measurements based on the Zeeman effect. A potentially useful diagnostic for the turbulent magnetic field is based on the Hanle effect, which describes various modifications of the scattering polarization by magnetic fields. The main effect, when observing near the Sun’s limb, is Hanle depolarization, which is the reduction of the polarization amplitudes in the presence of magnetic fields. We employ the Hanle effect in both atomic and molecular lines to investigate variations of the turbulent field, spatially, with the location on the Sun, and temporally, with the phase of the solar cycle. Realistic three-dimensional models of the solar atmosphere from numerical simulations shall help us in the correct interpretation of the Hanle measurements.

**Fundamental processes on small scales**

The solar atmosphere serves as a laboratory for radiative magneto-hydrodynamics in which fundamental interactions between magnetic field, plasma, and radiation can be studied.

**Magnetoconvection and turbulence**

Origin, dynamical structure, and significance of the weak magnetic field that is found in the interior of supergranulation cells—the inter-network magnetic field—are yet poorly understood. Here, high-precision polarimetric measurements based on the Zeeman and Hanle effect with future large aperture ground-based solar telescopes and advanced polarimeters (e.g., ZIMPOL3 or future fast polarimeters at GREGOR) promise progress in revealing the nature of the inter-network magnetic field. Is it intrinsically weak, or does it consist of fibrils of strong fields? Is it isotropically distributed and homogeneously turbulent, or does it have a preferential (horizontal) direction as is suggested by various numerical simulations? A fundamental process of MHD turbulence concerns the interaction of vortex tubes, which have been observed to form at the edges of granules, with the magnetic field. Is such interaction the cause of the tiny intergranular jets that are observed in Ha?

Observational investigations must be complemented by numerical simulations for a reliable interpretation of the measurements. With numerical simulations we also want to address the role of magnetic pumping in relation to the turbulent dynamo and investigate the origin of the weak magnetic field. Is it indeed locally generated by a turbulent dynamo, or is it a remnant of ephemeral active regions, or recycled large-scale magnetic flux, or a combination of such effects? Numerical simulations shall also be employed to accurately quantify the magnetic contribution to the Hanle depolarization.
**Intensification and dissipation**

Besides the ubiquitous weak magnetic field, locations with strong magnetic fields exist in the photosphere of the quiet Sun. Several processes have been suggested by which kilogauss flux concentrations may form, but it is still not clear which of these processes prevail in reality. Observational evidence for the convective collapse scenario has been reported by several observers. However, these measurements do not unambiguously prove that this magnetohydrodynamic instability is truly the driver for the magnetic field intensification. Intensification by dynamo action or by thermal relaxation are alternative scenarios. We plan further observational investigations using the high spatial and temporal resolution capability of the GREGOR telescope and realistic numerical simulations of near surface magnetoconvection, which should yield a solid statistical basis for comparison with observations. The disintegration of magnetic elements and their dynamic interaction with the surrounding convection and with magnetic elements of opposite polarity is also of interest. Some magnetic elements show substructure in the form of brightness striations, which may be the result of the magnetohydrodynamic exchange instability. Their wave number and growth rate can be influenced by diffusion effects, which poses a crucial test for the simulations and the limits for the MHD approximation in the solar photosphere.

**Energy transport**

A central theme of photospheric and chromospheric processes on smallest scales is the transport of mechanical energy into the upper layers of the atmosphere. How does it take place and how exactly influence magnetoconvective processes the chromosphere? It has been shown with the help of numerical simulations that vortical motions in the surface layers of the convection zone generate swirls in the chromosphere via magnetic coupling. We seek to directly observe this process. While past measurements of the vector magnetic field in chromospheric lines with POLIS failed because of lack of sufficient photon flux, new attempts will be done with GREGOR employing its four times higher light collecting power and its improved polarimetric system. The goal is to measure the vector magnetic field in the photosphere and the chromosphere simultaneously and with high cadence in order to collect evidence on the mechanical energy transfer associated with the transition from the photospheric to the chromospheric magnetic field. In particular, the enhanced chromospheric emission of the magnetic network is a long standing question that shall be addressed.

On the theoretical side, it is planned to improve and extend our three-dimensional holistic simulations from the convection zone to the chromosphere. With these we hope to gain understanding of the three-dimensional thermal and magnetic structure and of the magneto-acoustic wave propagation on the smallest scales in the chromosphere.

**Software development**

To achieve the above-mentioned goals, a significant effort is being undertaken in developing advanced computer programs. Chiefly, codes for the numerical simulation of radiation magnetohydrodynamic processes and for radiative transfer diagnostics are developed. Principal aim is to simulate solar and astrophysical processes with a sufficiently high degree of realism to enable the production of synthetic observables for
the direct comparison with real observations. Another aim is the development of efficient inversion methods for the derivation of physical quantities from observational data.

Typically, the software development at the Kiepenheuer-Institut is carried out in cooperation with research groups of other research institutes. Computer codes developed elsewhere are adapted to the specific problems at hand. Developments in the area of numerical (magneto-) hydrodynamics and radiative transfer are being monitored and active participation in the field provides hands-on experience with the most suitable methods for each problem. Furthermore, specific software for the analysis and visualization of simulation data (e.g., for the production of synthetic observational data) and for the reprocessing of inversion results are being developed.

**Formation and decay of sunspots and related magnetic structures**

Sunspots play an outstanding role in astrophysical research, since they provide a direct observation of the energy transport in magnetized plasma, at all their characteristic scales. As sunspots are visible manifestations of concentrated magnetic fields, the difference in brightness of the umbra, penumbra and granulation is due to the influence of the magnetic field on the convective transport of energy. The details of the relevant processes remain in many respects enigmatic. Thus, sunspots still represent one of the greatest puzzles in solar physics – their structure, energetics, dynamics, formation and decay remain unclear. The central goal of the sunspot research is to gain understanding of these processes in order to develop a self-consistent magneto-convective sunspot model that can be verified by means of dedicated observations. For this task, it is essential to understand how the dynamic small-scale structure within sunspots generates a coherent, large-scale and long-lived stable sunspot.

Figure 3: Sunspots are the most conspicuous manifestation of magnetic field on the solar surface. A sunspot formed in active region AR 11024 on the southern hemisphere on July 04, 2009. The figure displays six snapshots that have been recorded in the G Band (molecular band of the CH molecule around 403 nm) with the German Vacuum Tower Telescope on Tenerife. Adaptive Optics and Speckle methods have been used to achieve a spatial resolution better than 0.3 arcsec. The images have been reconstructed with the Speckle Interferometry package KISIP, and have been recorded using the adaptive optics system KAOS at the VTT.
Sunspot evolution

A crucial ingredient in understanding the magnetism of stars and the Sun is the formation, evolution, and decay of sunspots. How does the magnetic field emerge to the surface, and how does it gather to form sunspots and other magnetic structures? Emerging magnetic bipoles are observed to merge with the corresponding polarities, increasing the magnetic flux of active regions, and forming dark pores. Eventually, the penumbra forms around pores, which henceforth is called umbra. Various small-scale features, like penumbral filaments, umbral dots, and light bridges appear during the formation of the sunspot. The underlying physical processes await a consistent understanding. The spot formation is accompanied by the formation of large-scale flow fields in and around the spot. Detailed measurements of these fields will be crucial for our understanding of sunspot structure.

Besides the goal to understand the structure of a stable sunspot, we aim to answer the question on how sunspots form so rapidly, how they evolve, and also how they finally decay. Despite the progress in our understanding of solar magnetic fields, the scenario of sunspot evolution is not understood. What is the fate of the magnetic flux of decaying magnetic regions? Is the flux annihilated? How much of the flux is advected towards the poles? Is there any kind of flux recycling? The answers to these questions will provide a link between small-scale magnetoconvective processes and the large-scale solar magnetic activity.

Figure 4: Four sets of spectropolarimetric maps obtained at the VTT describe the formation process of a sunspot penumbra: (1) At 08:50, the field strength outside the continuum boundary of the spot is significant, while at 11:51 the boundary of the spot in continuum is very close to the boundary in magnetic field strength. (2) Penumbral filaments and penumbral areas are associated with large inclinations. The inclinations that are visualized in the third column are inclinations of the magnetic field vector relative to the line-of-sight. (3) During the formation process, the flow map exhibits alternating directions. Finally, the map at 11:51 shows a ’regular’ Evershed flow pattern. (4) The magnetic field strength in the light bridges increases with time. According to VTT observations, 3 days later, the light bridges also disappear in the intensity maps.
**Umbra**

The dark cores of sunspots, the umbrae, harbor the strongest magnetic fields at the solar surface (about 0.3T). Such a strong field suppresses the energy transfer via convection, leading to a cooler temperature in the umbra. The largest umbrae have a diameter of more than 20 Mm, and usually the cores of such big umbrae show regions of even lower continuum intensity. Large sunspot umbrae can persist for several weeks.

Umbral dots (UDs) and light bridges (LBs) are the common types of fine structure seen inside sunspot umbrae.

UDs are point-like brightenings in the umbra with a lifetime of a few minutes and typical dimensions of about 0.2-0.5 Mm. Smaller umbral dots are more uniformly distributed over the umbral surface than bigger dots. In large umbrae, there are usually dark nuclei in which there are no large UDs. The reported Doppler velocities in UDs are not consistent. The generic explanations of UDs are field-free intrusions of hot plasma as a result of convection. According to this model, this phenomenon only affects the lower solar atmosphere.

Light bridges are elongated areas in the umbra with an enhanced intensity. Most LBs are segmented along their length, with bright segments resembling tiny granules separated by narrow dark lanes oriented perpendicularly to the axis of the bridge and with a narrow, central dark lane running along the axis of the bridge. The magnetic field vector in the LBs is more horizontal than in the surrounding umbra. The measured magnetic field strengths in the UDs and LBs are about 1000 G smaller than in the umbra.

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Figure 5: Hinode observation of a sunspot at disk center with a spatial resolution of 0.3 arcsec.

a) Continuum intensity at 630.1 nm. Visible is the dark central umbra with faint umbral dots surrounded by the semi-dark penumbra consisting of radially elongated bright and dark penumbral filaments. b) Dopplergram showing up- and downflows in the penumbra. Upflows are mainly located in the inner penumbra, while downflows prevail at the outer penumbral boundary. These up- and downflows can be interpreted as the sources and sinks of the Evershed flow. c) Linear polarization, mimicking the transverse magnetic field. It is apparent that a significant amount of the magnetic field within the penumbra is parallel to the surface. d) Circular polarization representing the longitudinal magnetic fields. The filamentary structure known from the intensity images reappears. This hints at strong changes of the inclination of the magnetic field on scales of less than 1 arcsec.
Oscillations of velocity and intensity in sunspot umbrae have been observed for decades. The dominant periodicities are around 2-3 min, 5 min, and about 20 min. In the umbral chromosphere and transition region mainly periods around 2-3 min are found. These are partly a resonant oscillation of the spot itself and partly caused by the propagation of photospheric 3-min oscillations. Periods of 5 min and 20 min are, however, dominating at photospheric levels and seem to represent the passive response to the forcing of the spot by the 5-min oscillations in the surroundings.

The propagation of such waves of varying periods has been studied recently at different heights in observations and simulations. The transition between the linear and non-linear wave regime has to be located between high photospheric lines (e.g., Si I 1028.7 nm) and chromospheric lines like Ca II H. It is not clear yet if the magnetic field of sunspots also oscillates. Results from Advanced Stokes Polarimeter measurements showed variations of only a few Gauss in the field strength and a few degrees in the field inclination. This is partially in agreement with near infrared measurements. In addition, the study of waves in sunspots is important as a possible reason to sustain the radiative energy loss of the umbra in higher layers of the atmosphere (chromosphere and corona).

Our umbral research focuses on the details of the physical nature of umbral fine structure and the umbral energy transport mechanisms. Since convection is partially suppressed in the presence of the strong magnetic field in the umbra, other sources of energy, e.g., dissipation of magneto-acoustic waves, can play a role. Whether or not the primary energy transport mechanism is convection depends on the internal topology of umbral fine structure. We need to clarify the importance of different processes that sustain the umbral radiative loss and their relation to the umbral evolution and large-scale sunspot topology. This will improve our understanding of the way sunspot umbrae trigger energetic events like solar flares.

We plan to investigate the magnetic topology and organization of the umbral fine structure, i.e., umbral dots and light bridges. Compared to the lifetime of sunspots, the fine structure has a much shorter timescale. However, the mere existence of such a fine structure (i.e., hot plasmas) in the cold umbrae shows that even the largest sunspots cannot fully block the convection. We perform quantitative high-resolution spectro-polarimetric observations to infer the thermal, magnetic, and flow properties by taking advantage of inversions of the Stokes profiles. The simultaneous inversion of several spectral lines forming in different layers of the atmosphere provides reliable estimates for the physical parameters and for their gradients. We study the temporal evolution of individual structures and the properties of the global magnetic field in the umbra. The evolution of the magnetic flux will be studied from the flux budget. These results will be compared with 3D radiative magnetohydrodynamics (MHD) simulations.

**Penumbra**

The penumbra of a sunspot is a fascinating phenomenon featuring complex velocity and magnetic fields. It challenges both our understanding of radiative magneto-convection and our means to measure and derive the actual geometry of the magnetic and velocity fields. Spectro-polarimetric measurements reveal that the penumbra is inhomogeneous with depth, in the magnitude and direction of the velocity as well as in the strength and inclination of the magnetic field. Yet, many details of the small-scale geometry of these fields are still unclear, and their nature awaits a consistent explanation.

We will perform such simulations of radiative magneto-convection with COSBOLD and compare the results with spectro-polarimetric measurements at highest possible spatial and spectral resolution from instruments at the VTT and GREGOR as well as at the SOT on board HINODE and the IMAX on board SUNRISE. With our expertise in analysis, interpretation and inversions of spectro-polarimetric data, we expect to advance our understanding of the penumbral fine-structure.

**Subsurface structures and flows**

The velocity and magnetic field in the solar interior are the basic ingredients for the solar dynamo. Revealing the meridional circulation, the subsurface structure of sunspots, and the dynamics of rising fluxtubes are the milestones towards a self-consistent picture of the global solar activity. The seismic probing of the subsurface will be crucial to forecast solar activity and to properly connect the processes on the Sun to space weather phenomena.

**Magneto-atmospheric seismology**

Small and large-scale magnetic fields, e.g. in form of sunspots and pores modify seismic waves, since the latter can be converted to magneto-acoustic waves in the presence of strong magnetic field concentrations. This effect happens predominantly in those parts of the surface layers and lower solar atmosphere where the Alfvén and sound speed are equal. As a result seismic waves lose their energy and experience phase shifts, which renders the correct interpretation of seismic measurements inherently difficult.
Measurements of the process of wave conversion and phase shifting at multiple heights in the solar atmosphere with instruments that provide a high spatial and temporal resolution bears the promise to correct for this effect in the helioseismic techniques and in turn to provide internal structure information on the magnetic fields.

For space weather predictions it is important to relate sub-photospheric processes to events above the photosphere. For example, it is still unclear what triggers flares, or how coronal loops are anchored in the atmospheric layers of the Sun. Recent helioseismic measurements of the flow gradients show indications for a relation to flare activity.

High-frequency waves escape the solar interior into the solar atmosphere. There they interact with the magnetic field of small and large structures through reflection, transmission, and mode conversion, and may help to indicate mechanisms that trigger large-scale events like flares.

Helioseismology with SDO data will allow us to link the processes at the surface to what is happening beneath the surface. By extending helioseismology to the layers above the solar surface, more information about the properties of the solar atmosphere will be obtained. This, however, requires helioseismic observations that go beyond the data sets delivered by current helioseismic facilities including SDO. The requirements are Doppler maps of the Sun in multiple lines and at a higher temporal cadence. Our studies of wave propagation through a magnetically structured complex solar atmosphere using the COBOLD code helped selecting optical spectral lines for detecting the interaction of seismic waves with magnetic structures. Now we are carrying out observation campaigns at the VTT on Tenerife with the recently installed instrument HELLRIDE (Helioseismic Large Region Interferometric Device) to obtain data sets complementary to SDO data. Our goal is to establish links between the processes measured seismically below the solar surface and the related processes in the solar atmosphere as well as the detailed mechanisms of energy transport by acoustic waves. These studies will provide important input for the development of SPRING (Solar Physics Research Integrated Network Group), a new ground-based network of solar telescopes, which will offer a platform for instruments devoted to synoptic observations of the Sun.

Figure 6: Acoustic power of seismic waves crossing an annular region with 60 Mm inner and 80 Mm outer radius around a sunspot. Waves running towards the sunspot (left) show a stronger amplitude than the waves that leave the sunspot (right), which partly lost their energy to magneto-acoustic waves.

Figure 7: The etalons of the Fabry-Pérot interferometer (left) and the filter-shifting matrix equipped with two narrow-band filters and a reference laser (right) of the HELLRIDE instrument installed at the VTT.
Large-scale magnetic fields on the Sun

Strong shear flows in the solar interior are often discussed as possible locations for dynamo action. By means of helioseismology, two such zones have been identified: the tachocline at the bottom of the convection zone, where the latitude-dependent differential rotation transits into a uniform rotation of the Sun’s core, and a radial shear zone near the solar surface. It is assumed that a self-excited dynamo produces a complex magnetic field in the tachocline, which after rising through the convection zone manifests itself at the surface in the form of the observed activity features, like sunspots and prominences. We are aiming at obtaining insight into mechanisms of the global dynamo on large scales and at investigating the structure of the tachocline as an essential ingredient of the solar dynamo.

Mechanisms of the global dynamo

For understanding the physical mechanisms, local and global three-dimensional numerical simulations of the solar convection zone including the upper and lower boundary layers bordering the radiative zones will be needed. We plan to simulate the angular momentum transport while ensuing the differential rotation and the globally acting dynamo process. This will provide insight into the flux-tube system, which is presumably produced at the base of the convection zone, and its eruption to the surface and the formation of sunspots. Taking into account self-consistently the dynamo energy balance will enable a better understanding of the connection between the solar irradiance variation and the solar dynamo.

The structure of the tachocline as an essential ingredient of the solar dynamo can only be accessed by helioseismology methods. However, seismic inferences on the solar interior are limited by the spatial resolution of the Dopplergrams. The acoustic wave vector is mainly radial at the solar surface. Due to line-of-sight effects and foreshortening, the oscillation signal is best measured at disk centre and diminishes towards the limb. In Dopplergrams from the GONG and SOHO/MDI instruments the oscillation signal strongly decreases beyond a heliocentric angle of 60° away from disk centre, which is why helioseismic analyses were restricted to an area of 60°x60° centered on the solar disk. More severe, the restricted spatial extension limits the maximum wavelength of the oscillation modes. Because only modes with large wavelengths penetrate deeply into the Sun, local helioseismology was limited to a shallow region extending 20 Mm below the solar surface. Only newer data from SDO/HMI allows resolving the seismic signal to greater heliocentric angles of approximately 80°. We have started to carry out seismic analyses of the deep solar interior by new methods of global helioseismology that go beyond the standard frequency analysis, and by local helioseismology methods that are adapted to work with both the lower resolution data from GONG and MDI and the high-resolution data from SDO. These methods promise an improved seismic investigation of the structure of the tachocline and inferences from the structural and temporal changes at the bottom of the convection zone on its relation to the generation and the structure of the global magnetic field.

Figure 8: The radial (top) and horizontal (bottom) components of the Sun’s meridional flow as measured by cross-spectral analysis. Left column: Theoretical model and the seismic reconstruction. Right column: Seismic measurement based on six years of MDI data.

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Meridional circulation

One of the processes that are of major interest for the deep seated dynamo is the meridional circulation, which is a large-scale flow observed in both hemispheres of the solar surface. The meridional circulation is a key process in most flux-transport dynamo models. Hence, measurements of this flow are direly needed. The difficulty is that the effect of the meridional circulation on the solar oscillations is very small and is strongest at the surface, which is why it was seismically measured only in the outer 15 Mm of the Sun and no clear evidence for a return flow was so far found. Recently we have shown that the return flow should be observable with helioseismic time series that cover more than one year; not with standard frequency analysis, but with cross-spectral analysis that measures the coupling of the oscillation amplitudes due to the flow. We are now tailoring specific data analysis tools that are sensitive to such effects. The first results give promising results and allow measuring the large-scale meridional flow through the outer 150 Mm of the Sun. Long enough time series of oscillation measurements were recorded by the instruments of the Global Oscillation Network Group (GONG) or the Michelson Doppler Imager (MDI) aboard the Solar and Heliospheric Observatory (SOHO). In addition NASA’s Solar Dynamics Observatory (SDO) delivers Doppler velocity maps of the solar surface in an unheard-of volume and with better resolution. We will carry out an analysis of the existing long and contiguous time-series to exploit the full information content about the solar convection zone in these data. Such an approach allows obtaining the sensitivity for a global view on the structure of the meridional circulation throughout the whole convection zone by averaging more than 10 years of GONG and MDI data, and measuring the structure and temporal variation of flows in the solar interior during the rise and decline of solar activity.

Roots of sunspots

Sunspots have strong effects on solar oscillations, e.g., the amplitude, phase, and the travel time of seismic waves are altered near active regions. This in turn can be used to obtain a seismic image of the rooting of sunspots. We will employ numerical models of the solar convection zone, and magneto-hydrodynamic simulations of rising flux-tubes and sunspots to calculate the effect of such perturbations on the full seismic wave field. This will help to develop seismic methods that are most sensitive to the quantities under study. The inferred seismic signatures from GONG, MDI, and SDO data will then help to decide on the structure of a sunspot, i.e., whether it is monolithic or a cluster of fluxtubes.

Relation of surface activity to subsurface layers

We also want to probe the convection zone for fluxtubes when they approach the solar surface. Local helioseismology methods will be used to obtain synoptic maps of the solar interior over many months. This will allow tracking the rise of magnetic flux tubes, determining the anchoring of activity features, e.g., sunspots and prominences, and measuring temporal variations that are related to the dissolution of sunspots or the origin of flares. Again, numerical simulations will be used to produce artificial data that allow testing new data analysis tools for specificity and sensitivity.

Seismic noise generated by acoustic events in the intergranular lanes is itself scattered at supergranules and large granules. With SDO, the solar surface Dopplergrams achieve a high-enough resolution to study this wave scattering. Studying these scattering processes at a large number of supergranules by local helioseismology will allow deriving the sound speed and flow profiles in average supergranules and large granules.

Signatures of the global activity

Four hundred years of sunspot records is the best known data set for studying the evolution of the solar dynamo. Yet, new sets of observations found in the historic literature, especially around the Maunder minimum, provide new opportunities for studying the solar dynamo in its extreme appearance. We will apply our previously elaborated techniques to new data sets and obtain characteristics of the solar cycle, which will be compared to the current models. Also, other indices of solar magnetic activity collected more recently will be analyzed for studying the coherency of various patterns at different heights in the solar atmosphere as well as in the heliosphere and Earth atmosphere.

Furthermore, we are planning to undertake a major study of the sunspot butterfly diagram, with the emphasis on its fine structure, variability with the overall level of the solar activity and differential rotation. This will produce novel constraints for the solar global dynamo theory.

Finally, by analyzing the existing GONG, MDI, and SDO data bases we will set up a seismic catalogue of activity phenomena, from which we will be able to carry out statistics on the subsurface structure of activity features. Such studies are important for developing seismic tools that allow a prediction of the appearance of solar activity.
Solar full-disk observations

For full-disk observations we employ the telescope ChroTel, which has been operational since 2009. It provides narrow-band images of the full Sun in Ca II K 393.3 nm, Hα 656.3 nm and He I 10830 nm, with a spatial resolution of down to 2 arcsec and a cadence of down to 1 minute. The He channel provides filtergrams at seven wavelength positions, allowing a reliable determination of the chromospheric Doppler shifts. Together with the other channels we should be able to obtain 3D velocity fields of various structures. One goal is to investigate the chromospheric Doppler shifts through the He channel during global disruptions of the corona leading to Moreton waves, well observed in Hα. Combining the He and Hα data we will also investigate the flow structures in large prominences, which is not possible with high-resolution telescopes because of their limited field-of-view.

Continuous, long-term, consistent, and reliable solar data are a foundation for useful predictions of solar activity and space weather. An effective strategy to obtain nearly continuous synoptic solar data is the use of a ground-based network of identical observing instruments geographically distributed so that gaps from night time, weather and instrumental problems are reduced. There are currently a number of new scientific research directions in solar physics that motivate the desire for a new ground-based network. For example, there is a growing need for multi-wavelength measurements to provide observations of wave propagation and the vector magnetic field as a function of height in the solar atmosphere. For helioseismology we know that inclined magnetic fields in the solar atmosphere convert the acoustic waves into various types of MHD modes and change the apparent phase of the waves, which may lead to incorrect predictions regarding the sub-surface structure below active regions. For magnetic field measurements it is essential to know the direction and strength of the field above the photosphere for accurate coronal field extrapolations, and to reliably remove the azimuth ambiguity. Our understanding of the generation, transport and evolution of the solar magnetic fields would make significant progress with the availability of continuous long-term multi-wavelength observations. In addition, irradiance measurements such as those provided by the PSPT (Precision Solar Photometric Telescope), which are important for climate research, would be improved with additional spectral bands and more continuous coverage.

Given this considerable interest in a new synoptic network in Europe, an instrumental concept will be designed within the next year. The SPRING (Solar Physics Research Integrated Network Group) work package in the recently funded SOLARNET program (http://www.solarnet-east.eu/) and led by KIS is a first step towards such a new network for solar physics.

In due time, when the VTT has reached its “end of life” as a forefront instrument for high resolution observations, one might consider integrating it in the SPRING network and extend its useful life by a significant number of years.

Chromospheric heating and dynamics

One of the outstanding problems in solar (and stellar) physics is the unexpected increase in temperature as a function of height in the outer solar atmosphere. How the energy is generated and transported from the photosphere into the chromosphere and corona is a long-lasting debate, the so-called chromospheric and coronal heating problem.

While various mechanisms (acoustic waves, Alfvén waves, magnetic reconnection, electric currents, etc.) have been investigated for decades, no real consensus exists as to which are the main responsible ones. At KIS theoretical models are being developed and experiments are being carried out aiming at narrowing down the list of possible candidates and to establish the contribution of these mechanisms to the total amount of transported energy.

Waves

The solar atmosphere is a density-stratified medium where waves generated by the turbulent convective motion in the photosphere can propagate into the chromosphere. Potential candidates for transport and dissipation of energy in the quiet solar atmosphere, which do not involve magnetic fields, are acoustic waves and internal atmospheric gravity waves.

At KIS we investigate the signatures of these propagating waves. Observations suited for estimates of wave energy fluxes in the solar atmosphere are commonly attainable at the VTT. Velocities from 1D and 2D time series in spectral lines formed in different atmospheric layers can be retrieved. For the interpretation and estimates of energy fluxes, the equations of wave propagation in the solar atmosphere are considered assuming adiabatic waves in an isothermal atmosphere. Finally, power, phase, and coherence spectra and estimated energy fluxes in acoustic and gravity waves can be determined from the velocities measured in the spectral lines.

Analysis of GFPI/VTT and TESOS/VTT data performed at KIS resulted in significant energy fluxes in short-period acoustic and gravity waves detected in the mid photosphere and low chromosphere, demonstrating the
important role of waves in the transport of energy in the quiet Sun atmosphere.

An outstanding result obtained from higher resolution IMaX/SUNRISE data was the large energy flux in short-period waves, twice the value determined in previous works. These large values were never reported before, most likely due to limited spatial resolution. 3D simulations also show a decrease in the measured wave power when degrading the spatial sampling. Therefore, since most of the acoustic power is generated at the smallest scales in the quiet Sun, high spatial resolution is mandatory for its detection.

Like acoustic waves in the nonmagnetic atmosphere, magnetic waves can also transport energy only if their frequency exceeds certain cutoff values. So far, these frequencies could be calculated in closed form only for isothermal atmospheres. By using advanced mathematical techniques, we were able to determine the cutoff behavior in the nonisothermal solar atmosphere for both torsional and kink Alfvén waves along magnetic flux concentrations. We intend to expand these calculations to other wave types and to compare them to high spatial resolution observations, in order to assess their potential contribution to the heating of the upper solar atmosphere.

In the presence of inclined magnetic fields, waves of lower frequency can propagate and also contribute to efficiently transport energy in the solar atmosphere. Moreover, the presence of magnetic fields converts acoustic waves into a variety of magneto-acoustic ones (i.e., slow, fast, and Alfvén waves) and they may further interact with gravity waves. Therefore, the question arises where and how wave interaction takes place and how their propagation characteristics influence helioseismic diagnostics and the heating of the chromosphere and the corona. The theoretical group at KIS
addresses these questions employing three-dimensional magnetohydrodynamic simulations.

The experimental solar physics group at KIS plans to carry out similar analyses of time series of very high spatial and temporal resolution taken with GREGOR, Sunrise II and HELLRIDE/VTT to (1) confirm these findings, (2) to study in detail the (turbulent) phenomena triggering energetic processes, and (3) to extend the study to magnetic areas (network and sunspots) by studying the spectropolarimetric signature of these waves. A major step forward in the debate on waves generated in sub-photospheric layers as a mechanism for the heating of the upper layers is expected from ATST data, for which KIS is constructing a visible tunable filter in exchange for guaranteed observing time layers.

**Small-scale magnetic reconnection**

Magnetic reconnection occurs when magnetic field lines of opposite polarity meet and the energy stored in the magnetic field lines is released into thermal and kinetic energy. This mechanism can therefore contribute to the heating of the chromosphere and corona. We know that regions previously thought to be void of magnetic fields, such as the solar internetwork regions, do harbor a significant portion of the solar magnetic flux in the form of small scale magnetic fields. If the magnetic field in these regions undergoes any kind of reconnection, it could contribute significantly to the heating of the outer atmospheric layers.

The detection of reconnection events in the internetwork is ultimately linked to our ability to detect magnetic fields at the smallest possible scales. This poses an instrumental and observational challenge, as our ability to detect magnetic fields strongly depends on the signal-to-noise of the observations, which decreases as we observe smaller and smaller structures. The combination of large aperture telescopes like GREGOR and Sunrise with high-order adaptive optics systems will allow us to obtain high signal-to-noise observations at scales smaller than 0.1 arcsec.

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**Figure 11:** Three snapshots of a M2.5-class flare observed on June 7th, 2011 with the AIA (Atmospheric Imaging Assembly) instrument on-board the NASA satellite Solar Dynamics Observatory (SDO). The flare was followed by a filament eruption and a coronal mass ejection (CME).

**Figure 12:** Four snapshots of a M6.5-class flare observed on April 11th, 2012 with the ChroTel instrument at the Vacuum Tower Telescope in Izaña (Tenerife). This telescope was built and is operated by the Kiepenheuer Institut für Sonnenphysik. Each tickmark in the image corresponds to about 10 thousand kilometers (approximately the Earth’s diameter).
Flux emergence, flares, CMEs

Solar energetic events (X and M class flares, coronal mass ejections) are the most striking manifestation of the solar magnetic activity. Coronal mass ejections and solar flares occur over large regions of the solar surface, oftentimes encompassing several thousand kilometers. These events have been recognized as potentially having an important economical impact on our society. They can have disastrous consequences for satellite communications and cause power blackouts, interrupt cell phone communications, GPS tracking, and cause delays or re-routing of polar flights.

Predicting these highly energetic events is, therefore, of great interest. We know that energetic events are triggered by unstable magnetic configurations. Such configurations appear as the magnetic flux emerges from the convection zone and is transported into the solar atmosphere, where it interacts with the preexisting magnetic field. The reconnection region is usually characterized by the presence of large electric currents that dissipate the energy stored in the magnetic field into kinetic and thermal energy.

Current attempts to predict the onset of flares and coronal mass ejections employ proxies of the magnetic field topology, such as broadband imaging, magnetic helicity and free energy obtained from field extrapolations, as well as fractal or intermittency indexes. All these proxies are, in fact, simplified representations of the real magnetic topology in the solar atmosphere and consequently of limited prognostic value.

At KIS we are developing new techniques that will go significantly beyond the current state-of-the-art in this field. Stokes inversion techniques will allow to directly infer the three-dimensional topology of the magnetic field vector in the solar atmosphere in order to locate unstable regions. Furthermore, global and local helioseismology techniques are developed to predict the emergence of large concentrations of magnetic flux (i.e., sunspots) before they are visible on the solar surface, and even on the far side of the Sun.

The application of such techniques to high-quality data shall lead to improved forecasting capabilities and deepen our understanding as to how the magnetic field is transported from the convection zone into the outer solar atmosphere. KIS participates in several modern solar observatories and space missions that will provide the data required.

STARS

Obtain 3D tomography of stellar magnetic fields across the HR-diagram

A significant breakthrough in understanding solar activity can be achieved by expanding the analysis towards other stars. The spectropolarimetric diagnostics tested on solar magnetic structures are being now applied to obtain a 3D structure of stellar magnetic fields which are spatially unresolved and cannot be imaged directly. Our goal is to obtain magnetic tomography of atmospheres of stars of various masses, luminosities and ages, i.e. across the HR-diagram, especially its cooler part. A comparison with the solar magnetic structures (sunspots, faculae, magnetic network) will reveal an evolutionary scenario for the stellar magnetism.

In order to investigate the magnetism of cool stars and substellar objects, we employ our expertise in molecular spectropolarimetry which has been developed by us during the last decade. Using this technique we will focus on obtaining the strength of the magnetic field and its spatial and the temporal evolution on cool stars and substellar objects such as brown dwarfs and hot Jupiters. This information will help us to clarify the operation of the dynamo mechanism in fully convective low mass objects which is still poorly understood. In particular, we will investigate recently discovered radio pulsating brown dwarfs which apparently have active magnetospheres. We expect that similarly active objects can exists among hot Jupiters. Therefore, we will develop techniques to detect their magnetic fields too.

Expand and analyze long-term records of stellar cyclic activity

The activity of the Sun and other cool stars is caused by a magnetic field which often varies periodically – in the case of the Sun it is an 11-year cycle. The origin of such variations remains so far an unsolved puzzle for astrophysics. It is assumed that self-excited dynamos generate a complex, large-scale magnetic field in shear zones located in the solar and stellar interiors. An analysis of long-term records of stellar activity will provide observational constraints on and relation between such important dynamo parameters as the stellar rotation, cycle length, differential rotation, multi-cyclic activity, etc.

We have developed a novel technique that allows us to recover both spot latitudes and differential rotation
from continuous photometric time series. This helps to produce butterfly diagrams and synoptic charts for distant stars, similar to the solar ones. We will analyze immense Kepler and CoRoT data with this new technique and create an extensive database of stellar activity revealing a multitude of spot properties and activity cycles on stars as Suns. We will further combine this technique with asteroseismology data and investigate subsurface properties of active regions. The developed technique can also be used for the data analysis of new space missions such as TESS and others.

**Explore circumstellar environment and its influence on planet formation and evolution**

Planets are affected in various ways by stellar luminosity variations at all wavelengths as well as by the particle emissions associated with the stellar wind, coronal mass ejections, and flares. For instance, the solar EUV emission is highly variable and strongly affects the energy balance in the Earth’s thermosphere/ionosphere. Thus, the Sun-Earth system and the Solar system itself provide an exemplary model for approaching the general problem of the star-planet coupling.

We will investigate planets, moons and minor bodies in the Solar system to assess the influence of the solar activity on their evolution. The synergy of our expertise in the solar activity and in atmospheric physics will be the driving force of this research. In particular, we will focus on assessing the bulk composition of minor bodies by studying their tenuous exospheres. This will provide invaluable constraints for Solar system formation models.

The formation of planets around stars is a dynamic process. Over the course of a few million years, parts of the circumstellar gas and dust accrete onto the star, turn into planets, or dissipate in the form of winds and jets. Water is one of the most important species in star and planet formation and among most abundant molecules in the Universe together with H₂ and CO. We aim to detect and locate hot molecular clumps in a larger number of protoplanetary and debris disks and evaluate orbits of volatile-rich planetesimals. This will provide constraints on formation of terrestrial planets and will reveal promising targets for future organic searches in prebiotic water-rich environments. We will use the polarimeter InnoPol developed within the collaboration between KIS and UH/IfA and installed at the AEOS telescope on Haleakala, Maui. The next version of this instrument will be installed at the GREGOR telescope and will significantly enhance our observing program. This research is supported by the ERC Advanced Grant HotMol (2012-2017).

**Understand planetary atmospheres weathered by stellar radiation and activity**

Stellar light is the main source of energy for life on Earth, while the Earth’s atmosphere, oceans and magnetosphere shield organic molecules and life from intense UV radiation and high-energy particles. Detecting atmospheres on extrasolar planets is still challenging, while finding liquid water on the surface of a potentially habitable Earth-size planet is not yet possible.

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**Figure 13:** 3D structure of a starspot on a young red dwarf star (vertical cuts through the atmosphere). The temperature (left) and radial magnetic field (right) decrease with height, while the spot area increases. A strong entangled magnetic field fills space between spots in the lower photosphere.
However, volatiles in the atmosphere can be detected using transmission spectroscopy and spectropolarimetry. To advance our understanding of how planets acquire their atmospheres and in particular water vapor and how planet formation and stellar activity influence habitability, we will develop novel techniques for detecting and characterizing molecular species in exoplanets. The same techniques will be used for detecting exoplanetary magnetospheres. This research is supported by the ERC Advanced Grant HotMol (2012-2017).

**Polarimetric detection of exoplanets**

The study of an exoplanetary atmosphere and its composition is our sole key to determining whether an exoplanet is habitable or not. Observing an exoplanetary atmosphere remains a challenging task, thus raising the need for new techniques for their detections. There are only a handful of available methods of observing an exoplanetary atmosphere at this stage, mainly restricted to an exoplanets’ transit in front of its host star.

We aim at the development and application of innovative methods, namely polarimetric techniques, for detecting and characterizing exoplanets. The use of molecular spectropolarimetry for detecting exoplanets allows us to extend our search to non-transiting planets and to sample planetary atmospheres at various orbital phases. The results will then be analyzed together with previous results of transiting exoplanets.

Advantages of polarimetry also include its sensitivity to magnetic fields, which are largely unexplored in exoplanets, and may lead to the first direct detection of an exoplanetary magnetosphere.

Polarimetric signatures in observed spectra originate in the processes of optical pumping, scattering, and magnetic interactions in water molecules and various other molecular species. Since the observed polarization signature strongly depends on the composition of the atmosphere, detecting polarized molecular lines will allow comprehensive modeling of exoplanetary atmospheres. We will provide a synthesis of polarized molecular spectra under various physical and geometrical conditions, including magnetic field effects. This will create the basis for planning observations to find water, volatiles, and even organics in exoplanetary atmospheres, which are expected to show a huge diversity due to the different evolutionary history, the distance to the host star, and the formation location in the disk. Thus, we will provide a sensitive tool for detecting hot molecules in exoplanets and show how the analysis of polarized spectra can reveal their atmospheric composition and structure. We will use the polarimeters DIPol-2 and InnoPol installed at the AEOS telescope and in the near future at the GREGOR and PLANETS telescopes.
**Transiting exoplanets**

Detecting planets by observing stellar light variability due to planetary eclipse (transit) has become the most productive method for finding exoplanets thanks to multiple ground-based searches like HAT-P and WASP as well as space missions *Kepler*, CoRoT and in the near future TESS. Hundreds transiting planets are known to date. We collaborate with the Searchlight Observatory Network (SON) to observe transiting planets in various optical passbands in order to constrain models of their atmospheres.

During planet transits one can also observe linear polarization arising due to breaking the symmetry of the projected stellar disk. Such effect was predicted in the 1950th and was first detected in the eclipsing binary Algol. It strongly depends on the centre-to-limb variation of the scattering polarization in the stellar atmosphere. However, observational and theoretical studies of the limb polarization largely concentrated on the Sun. We expect that a larger limb darkening in cooler stars will cause a larger centre-to-limb linear polarization. Therefore, we will study limb polarization of stars hosting transiting planets. We will simulate centre-to-limb polarization of various stars and will predict polarimetric signals in different passbands. Using remotely controlled DiPol-2 polarimeters developed within the collaboration between KIS and UTU and installed at the SON telescopes we will try to detect such polarization on most promising targets. We will also measure centre-to-limb continuum polarization on the Sun in order to calibrate our theoretical predictions for other stars.

Figure 15: First measurements of the reflected light from an extrasolar planet reveal its blue color in the visible, similar to that of Neptune in the Solar system (the Neptune background image is from NASA).
TECHNIQUES

Offer efficient data reduction pipelines and analysis tools

It is nowadays clear that the astronomical instruments yielding the highest scientific output are those for which the developer provides up-to-date software packages and data-reduction routines. This permits the retrieval of data of the highest possible quality standards in an efficient and user-friendly manner. The need for these data pipelines is essential when dealing with modern, high-throughput instruments that require complex calibration procedures and deliver large amounts of data. This is the case for instruments such as TESOS (Triple Etalon SOLar Spectrometer), GFPI (GREGOR Fabry-Pérot Interferometer), GRIS (GREGOR Infrared Spectrograph) and LARS (Absolute Reference Spectrograph), in operation at the German solar telescopes at the Teide Observatory (Spain), and specially for next-generation instruments such as VTF (Visible Tunable Filter) to be developed by KIS for the 4 m class ATST solar telescope. These instruments demand a very deep knowledge about their inner workings, thus preventing non-expert scientists from efficiently exploiting the output. This can discourage scientists to consider the use of these instruments for their research interests.

The creation of the Center for Advanced Solar Spectropolarimetric Data Analysis (CASSDA project) as well as part of the SOLARNET project at our institute will address these issues.

CASSDA is fully funded by the Leibniz Association and it is running from 2013 until 2015. Its main goal is to provide the solar physics community with the most accurate spectroscopic and spectropolarimetric datasets observed at the German solar observatories. This will be achieved in several steps. First, the existing software libraries will be revised and unified to calibrate the data. Second, after the standardization of the data analysis procedure, the processed data will be automatically released to the scientific community through the Virtual Solar Observatory. Finally, CASSDA

Figure 16: Flow chart of the data management procedure developed in the framework of the CASSDA project.
will train young post-docs and PhD students to acquire expertise in the aforementioned instruments, observing procedures, and data handling.

The data analysis and procedures will include routines to calibrate the observables i.e., (1) to correct from instrumental effects, e.g., flat-field, correction for pre-filter curves and instrumental polarization, resulting in level 1 data, (2) to apply image reconstruction techniques to retrieve the highest spatial resolution, and (3) to recover the Stokes parameters, resulting in level 2 data. Level 2 data will be ready for scientific analysis.

In addition, Stokes inversion techniques will be implemented in order to infer physical parameters in the solar atmosphere (including the magnetic field vector), resulting in level 3 data, from the observed and calibrated Stokes vector.

The Stokes inversion codes employed will be the Very Fast Inversion of the Stokes Vector code (VFISV) and the Stokes-Profiles-INVersion-O-Routines (SPINOR). The former code employs the so-called Milne-Eddington approximation, in which the physical parameters are assumed to be vertically constant across the solar atmosphere. This assumption makes VFISV very fast, efficient and portable. It is therefore ideal to provide the observers with a reliable first-look to the physical parameters in the solar atmosphere as inferred from their data. This will allow them to make real-time decisions about their observing targets and sequence in order to maximize the scientific output of their next observation. Unlike VFISV, the latter inversion code, SPINOR, is able to retrieve the vertical dependence of the physical parameters through the solar atmosphere. This capability makes this code more appropriate for more detailed and final investigations. Unfortunately, its slow speed makes it unpractical for in-situ and fast analysis.

Inversion codes are the most reliable tool available to the solar physics community to infer the physical properties of the solar atmosphere from observations of the Stokes vector. This is done by solving the radiative transfer equation assuming a initial set of values for the physical parameters in the atmosphere (temperature, velocity, magnetic field, etc). The solution to the radiative transfer equation yields a theoretical Stokes vector (Figure 2), which is then compared to the observed Stokes vector via a $\chi^2$ merit-function. The initial set of physical parameters is then modified, through non-linear minimization algorithms, in order to produce a better fit between theoretical and observed Stokes vector (minimization of the merit function). The atmospheric parameters that produce the best match between the observed and theoretical Stokes vector is then assumed, provided that the solution is unique, to be the real one present in the solar atmosphere.

**Development and deployment of solar high-resolution techniques**

The goal of this work is to develop and deploy forefront instrumentation and data analysis methods for high-precision spectropolarimetry with a spatial resolution that approaches the diffraction limit of the new generation of solar telescopes whose apertures exceed the meter. Achieving this goal requires on-going fundamental research in specialized fields of optics and data analysis methods, in particular in the following areas:
• Wave Front Control, with the emphasis on image stabilization, adaptive optics, multi-conjugate adaptive optics and control algorithms

• High Precision Spectrographs, including FPI spectrograph development, grating spectrometer development and modeling of advanced optical components and systems

• Detectors, with the focus on camera readout and preprocessing systems, high throughput detectors and special detectors for spectropolarimetry

• Data analysis methods, including statistical image processing, and wave front estimation and deconvolution.

**Wave Front Control**

Basis for the present success of KIS in the area of wave front control is the development of an integrated environment for high-precision control of multi-element optical systems and wave front sensors, which is used in every project where optics are actively controlled. Currently deployed instances of this environment are the KAOS adaptive optics system at the VTT, the GAOS adaptive optics system at GREGOR, and the Sunrise CWS which has been in flown in 2009 and 2013.

The system includes the capability to merge several wave front sensor measurements in order to control several active optical elements such as mirror alignment systems, tip-tilt and deformable mirrors (DM) in a multi-conjugate configuration. There is collaboration between KIS, NSO and NJIT/BBSO for developing solar multi-conjugate adaptive optics (MCAO) for GREGOR, NST and ATST. The GREGOR MCAO system will be integrated into GAOS in the course of 2013/14. This development also forms the basis for MCAO on the European Solar Telescope (EST).

The goals of the Research Plan 2009-2013 (development of first-light and high-order AO systems for GREGOR, development of MCAO for GREGOR, design of MCAO for EST, development of the image stabilization system for SUNRISE and SO-PHI, collaboration of MCAO for ATST and site characterization research) have been mostly completed, a few are on-going.

The following goals are set for the 2013-2017 timeframe:

• GREGORs current High Order Adaptive Optics (HOAO) system GAOS includes a deformable mirror in the pupil conjugate with about 200 actuators. The MCAO system for GREGOR includes two additional deformable mirrors with conjugates at 8 km and 20 km along the line of sight which have 80 actuators each. The goal is to upgrade the system with deformable mirrors which represent the optimum in terms of number of actuators per area.

For the pupil conjugate DM, a 400 actuator mirror will be needed. The specifications for the high altitude DMs will be the result of ongoing tests and research with the existing MCAO system.

• A collaboration has been established with NSO and NJIT to develop MCAO for the NST at BBSO and for ATST. This will continue throughout the next five years.

• Research on atmospheric turbulence characterization, wave front sensing methodology, and optimal control of AO and MCAO systems. This is a continuing activity which is mostly carried out in the context of student projects as occasions arise. This activity is essential for pursuing new solutions and exploring new ideas.

**High-Precision Solar Spectrographs**

KIS operates several spectrographs with polarimetric capability at the VTT, including the echelle spectrograph, the Triple Etalon Solar Spectrometer (TESOS) and the Polarimetric Littrow Spectrometer (POLIS), all of which were developed in house.

The echelle spectrometer has been equipped with a laser frequency comb to establish a high precision absolute wavelength scale, a unique feature in solar physics, which enables very high precision measurements of line-of-sight motions in the solar atmosphere at visible and near-infrared wavelengths.

TESOS is a three etalon filtergraph that has been in operation since 1997. It was upgraded to a Stokes vector polarimeter in 2005 in collaboration with the University of Granada. TESOS complements the GFPI filtergraph at GREGOR at short wavelengths between 550 and 430 nm until the GFPI is equipped with a blue channel. TESOS also serves as a research instrument for the development of ATST-VTF.

The development projects for spectrometers like ATST-VTF need to be accompanied by a research program addressing fundamental instrumental questions. Various effects influence the design and performance characteristics of an FPI-based spectrograph and are a steep function of the instrument’s optical throughput. They affect design choices which can make an instrument unfeasible or too expensive. This is particularly the case for a new generation of large aperture solar telescopes.

Goals of the previous Research Plan were the study of the influence of etalons on the polarimetric properties of the filtergraph (completed), the initiation of a development program for large etalons (under way with the ATST-VTF development), and the development of a visible channel for the grating spectrograph of GREGOR (postponed).
Ongoing research activities which carry on into the period covered by this plan address issues arising from ongoing development projects and include

- The development of a precise physical optics model of etalon defects including variations of air gap and reflectivity to study their impact on the quality of the observations and on the requirements on data processing (PhD thesis).
- Development of a large aperture high precision etalon prototype for ATST with industry.

Future research activities to be initiated during this research plan period include development of a 2nd generation grating spectropolarimeter channel for the visible spectral regime at GREGOR.

**Detectors**

Solar physicists continue to rely on mainstream machine vision detector development and acquire typically the latest off-the-shelf camera technology. Because of the comparatively large flux, solar observations are photon noise limited rather than detector limited, so the technology decisive factors besides frame format and spectral response are intensity resolution (bits per pixel) and exposure control flexibility. During the past decade, KIS has relied on the market development and acquired off-the-shelf cameras with 1K - 4K pixel formats, and will continue to do so for general purposes.

In the context of high resolution in all essential domains – space, time and wavelength – combined with the need for high photometric precision it will become necessary to substantially improve detector technology beyond its current capabilities. The spectral response of today’s detectors is close to the quantum limit throughout the visible and near-infrared regimes, there is little room for improvement. One remaining issue is detector duty cycle, i.e., the fraction of open shutter time to total time. Recent commercial CMOS technology cameras achieve some 100 frames per second and make cameras with much better duty cycle feasible. Such a camera has been developed and integrated into TESOS to support real time monitoring of the performance and field dependence of adaptive optics compensation for high photometric precision spectroscopy.

Ongoing research activities include development of the capability for rapid readout and on-the-fly processing of large quantities of data. Much of this work will be integrated into experimental thesis work.

The real challenge for detectors in solar physics is high-precision Stokes vector spectropolarimetry, which requires a precision of 1 part in $10^3$ to $10^4$. The success depends critically on the proper combination of polarization modulation and demodulation, as accuracy and precision of Stokes vector measurements is plagued by many artifacts. It has become evident during the past years that the best solutions are detectors that implement the characteristics of ZIMPOL, which was developed at ETH Zürich. A collaboration exists between KIS and IRSOL to use ZIMPOL with GREGOR. Continuing this and entering into new collaborations to develop these detectors is a goal for the next five years.

**Image Restoration Methods**

The combination of adaptive optics with data restoration has vastly improved the high spatial resolution capability of solar telescopes, rendering them diffraction limited for a substantial fraction of observing time. Adaptive optics imaging always suffers to some extent from residual, dynamic errors which limit the resolution and photometric precision of the image in the partially compensated focus. Conventional and multi-conjugate adaptive optics have strong field-dependent residual errors beyond their fields of compensation, which for conventional AO is limited to just a few arcsec.

There are several methods that permit estimating and correcting residual wave front error, including (in ascending order of raw data input) phase diversity, multi-frame blind deconvolution and speckle imaging. All methods use short exposures as input data in order to restore the high-resolution content. Speckle imaging, which cannot handle static aberrations very well, benefits particularly from partial AO compensation, which reliably removes low order static and slowly varying error components. We have developed speckle imag-

![Figure 18: A decaying sunspot near the disk center observed with GREGOR BBI in May 2013 at 589 nm. This reconstructed image is based on 100 short (1 ms) exposures which were compensated with GAOS. Image processing with KISIP.](image-url)
ing to a point where field-dependent residual errors are reliably estimated and corrected, based on input data and adaptive optics system parameters, and a restored field of many arc minutes squared is possible.

The multiprocessor software package KISIP (Kiepenheuer Institut Speckle Imaging Package) includes the methods for statistical PSF estimation, extended to partial AO correction. The software package is a standard for solar speckle imaging worldwide. Diffraction limited performance is routinely achieved with meter-class telescopes based on broadband image data, and has recently been demonstrated with the larger telescopes NST and GREGOR as well.

Similar high resolution performance must be achieved with the very narrow spectral bands of spectroscopy. Existing methods which combine high spectral and high spatial resolution, based on restoration algorithms of simultaneous short exposures in broad and narrow spectral bands, are consistently limited to about half the diffraction limit, and analysis suggests that this has fundamental reasons. New data acquisition and analysis methods are needed to overcome this restriction.

Ongoing research activities in the area of image restoration methods include:

- Continuation of development of KISIP, focused on multiprocessor environments and further improvement of field dependent PSF estimation. A big goal is to boost KISIP’s performance to real time capability in order to produce the final reconstructed image while observing, by migration to GPU processing.
- Continuation of the development of high spatial resolution spectroscopy based on short exposures with TESOS and the GREGOR FPI.
- Extension of the current PSF estimation methods to a robust estimation of partially compensated long exposures.

Research activities which will be initiated during the next five years include improvement of current PSF estimation methods to include field dependence for high-order adaptive optics and multi-conjugate adaptive optics. These methods will be verified with observations with GREGOR and used to demonstrate high sensitivity, high spatial resolution spectroscopy. Much of this work has been accomplished in the context of PhD theses. This will continue to be the case.

**Instrumentation for non-solar high-precision polarimetry**

Investigating magnetic activity of stars and exoplanetary atmospheres requires continuous polarimetric observations, which are most efficient when instruments at multiple observing sites are employed. It is our goal to participate in international collaborations to establish a global polarimetric network of 1-2 m telescopes equipped with advanced polarimeters.

These polarimeters will be designed for maximal sensitivity to detect very small polarization signals. Our goal is to achieve a noise level in fraction of polarization of $10^{-5}$ and smaller. To reach this very high sensitivity the system has to be limited by photon-shot noise only which is the ultimate performance limit of every polarimeter. Therefore any other instrument noise and systematic errors must be smaller than the shot noise.

**Technology**

In 2011 we started a cooperation between KIS, University of Hawaii, USA, and University of Turku, Finland, to develop the new innovative polarimeters InnoPol and DIPol-2 and to employ them at telescopes available through the cooperation (e.g., PLANETS and AEOS telescopes, Haleakala Observatory, Maui; GREGOR night time, and other Canary Island telescopes; the Searchlight Observatory Network telescopes in Chile, New Mexico, Hawaii and Tasmania).

For imaging and spectropolarimetry our basic concept is to use a single beam design with a fast electro-optical polarization modulator in combination with a fast camera system. The single beam design avoids limitation of detector gain calibration because the different polarization states are recorded by the same pixels. Time dependent variation (e.g., seeing), the main limitation of a single beam instrument, will be minimized by fast modulation. Simulations have shown that the modulation frequency should be at least 200 Hz.

Detectors and modulators are the most critical part in the system. We will study the following technologies to get the most efficient detector modulator combination with minimal error sources.

**Detectors**

*Charge shuffling CCDs*

With this type of detector demodulation is performed on chip by charge shuffling between open and covered CCD rows. It is independent of the frame rate and therefore readout noise is not critical. The concept is best known from the ZIMPOL (Zurich IMaging POLarimeter) system that uses a masked CCD. But these special CCDs are complicated and very expensive to produce. An easier, much cheaper approach is to put a mask in a focal plane and image it onto the detector. We have already started with laboratory tests that show the concept could be a powerful system for low-
resolution spectra-polarimetry of bright stars, but it is rather limited for imaging polarimetry.

**EMCCDs**

EMCCD sensors have an additional internal gain register (electron multiplying register EM) which amplifies single electrons and therefore readout noise is not a limiting factor even with very fast read-out speeds. Current commercial cameras have a frame rate of 500-900 fps with a read-out area of typically 128 x 128 pixels. In 2012 we started with camera tests and will continue 2013 with the newest generation of these cameras. Because EMCCD cameras are off-the-shelf products we plan to use them for the first generation of our instruments.

**Low noise high speed CCDs (pnCCD)**

Recently MPS has developed a new polarimeter based on a specially designed low noise, high speed CCD sensor (pnCCD with 264 x 264 pixels, 850 fps, 2-3 e⁻ read out noise). Compared to EMCCDs the pnCCD sensor has a better quantum efficiency, and higher frame rates with a large frame size, but it could still be limited by the read-out noise for faint objects. We will study this concept as a possible alternative to EMCCD cameras.

**CMOS detectors**

In the past CMOS sensor technology has been developing rapidly and therefore it has become a good alternative to CCD sensors. Standard CMOS cameras already work with several hundred fps with a read-out noise of only a few electrons. The technique would potentially also allow on-chip demodulation (compared to charge shuffling CCDs, but without the drawback of a masked sensor) but these would require a special sensor design which is very expensive. We will explore this technology for possible use in future generation cameras.

**Modulators**

**FLCs**

We use ferro-electric liquid crystal (FLC) modulators, which are widely used for fast polarimeter projects. They can be used for a modulation frequency up to 1 kHz. Single devices are wavelength dependent and therefore we have to develop special designs for our broadband applications. They also suffer from small disturbing effects which have to be investigated carefully to achieve the highest polarimetric sensitivity.

**LCVRs**

Liquid crystal variable retarders are another modulator type commonly used in polarimeters. Standard devices are too slow for fast modulation, but recently a new type (Swift LCVR) has appeared on the market which is much faster. Our first tests showed that it is a promising technology, but the current devices do not yet meet all requirements. We are close in contact to the manufacturer with the goal to improve this technique.

**New instruments**

**InnoPol-1 at AEOS:**

In 2013 we are commissioning our first instrument at the 3.5 m AEOS telescope at the Haleakala Observatory on Maui. It is based on a standard EMCCD camera, a FLC modulator in combination with a curvature AO system and a coronagraph. The system allows us to get experience in real observation. The first science goal will be high-precision imaging polarimetry of proto-planetary disks with high resolution.

**GREGOR@NIGHT Imaging Polarimeter**

In 2014 as part of the GREGOR@NIGHT project we will build a similar instrument at the GREGOR telescope. The instrument will be equipped with the newest and fastest generation of EMCCD cameras and will be com-

![Figure 19: Night-time polarimeters InnoPol (top) and DiPol-2 (bottom).](image-url)
bined with the GREGOR AO system adapted for night time observation. One of our scientific goals will be high-precision polarimetry of solar system planets with high resolution.

**InnoPol-2**

For the time 2015-2016 we plan to build the next generation instrument. Based on the experience we got from the previous two instruments and our technology development this instrument should have improved camera and modulator technologies.

**DiPol-2**

The Double Image Polarimeter (DiPol-2) was developed in collaboration between KIS and University of Turku, Finland. It can provide a polarimetric accuracy of $10^{-5}$. It consists of three cameras providing simultaneous measurements in three bands (blue, visual, red). A rotatable super-achromatic $\lambda/2$ retarder plate modulates the relative intensity of the two polarized beams produced by the calcite crystal, with an amount proportional to the degree of linear polarization of the incoming radiation. The passband is divided by two dichroic mirrors into three beams. The fluxes of the two polarized stellar images in the three channels are measured with highly sensitive cooled CCD detectors. Several copies of this polarimeter are planned to be built and employed at the Searchlight Observatory Network telescopes, which are available to us through collaboration.
Visible Tunable Filter for ATST

US American research institutes are currently building the Advanced Technology Solar Telescope (ATST) under the direction of the National Solar Observatory (NSO). This world’s largest solar telescope has a free aperture of 4 meters and is designed for diffraction-limited observations in the optical and infrared spectral ranges and for coronal observations in the infrared spectral range. The selected site for ATST is Haleakala on Maui, Hawaii, where the coronal conditions were found to be excellent. According to current planning, the ATST will go into operation around. Equipped with adaptive optics and with modern focal instruments, it will be possible for the first time to sense solar physical processes near or at their dissipative scales and to directly test theoretical models, e.g., of the magnetoconvection in sunspots or small magnetic elements, as being developed at the KIS.

KIS considers participation in ATST to be necessary in order to maintain its outstanding role in solar research in the long term. KIS employees have been involved in the ATST site testing and in the drawing up of the scientific requirement catalog. Because of its long lasting experience in building and operating of solar spectropolarimeters, KIS was invited by the ATST consortium to contribute a tunable 2D spectrograph for visible wavelengths as first light post focus instrument for ATST. KIS successfully applied for funding for such an instrument from its funding agencies. The design is based on a triple etalon system with a free aperture of the etalons of 250 mm.

The total VTF budget (KIS base funding plus additional funding) sums up to about 6.9 Mio EUR over 8 years. The design and development phase of the Visible Tunable Filter VTF started in 2012. A conceptual design review was successfully held with the ATST team in spring 2012. The preliminary design review is scheduled for fall 2013. Commissioning of the VTF at the ATST is foreseen in 2017.

After commissioning the VTF instrument will be given to the ATST. In return, KIS scientists will receive a certain amount of guaranteed observing time during the first years of ATST operation.

Besides the VTF it is also foreseen that KIS contributes a full disc auxiliary telescope for ATST, based on the ChroTel design. Here the D&D phase is expected to start in 2014.

Every effort will be made to continue and intensify the traditionally good cooperation between KIS and NSO.

Instruments for solar space missions

Solar Orbiter

KIS participates in the development of the Polarimetric and Helioseismic Imager (PHI) of the Solar Orbiter mission. Solar Orbiter is a mission dedicated to solar and heliospheric physics. It was selected as the first medium-class mission of ESA’s Cosmic Vision 2015-2025 Program. The PHI instrument is part of the remote-sensing instrumentation of the Orbiter, led by the Max-Planck-Institute for Solar System Research (MPS) in Lindau. The Orbiter will approach the Sun in an eccentric orbit as close as 60 solar radii (0.28 Astronomical Units). The final orbit inclination of about 30 degrees with respect to the Ecliptic will allow – for the first time ever – direct measurements of the solar polar magnetic field. Launch is presently foreseen in 2017, and, after a three-year cruise phase, regular science operations are planned to start in 2020. The extended mission duration is about ten years and will end around 2027.

KIS develops the Image Stabilization System (ISS) for the PHI instrument, in cooperation with the University of Barcelona. The ISS is based on a correlation tracker and builds on heritage and experience with wave-front correction systems that were developed in-house for our telescopes on Tenerife and for the balloon-borne observatory SUNRISE. Our contribution to Solar Orbiter is funded by the DLR. Funding is presently secured until 2016, and follow-on funds covering the extended mis-
sion duration are foreseen at DLR and will be negotiated in due time. With the development of the ISS, KIS has gained technical and management skills specifically for space missions, and KIS has also built up adequate laboratory space – including a small clean room - for space hardware development.

During the years covered by this document, KIS will build and test various units of the ISS: engineering models, a structural model, a qualification model as well as the flight and flight spare models. Delivery of the latter two is foreseen for 2015. Subsequently, we will participate and support integration activities at ESA, on instrument and spacecraft level. First instrument commissioning activities will take place shortly after launch. In order to support this work, a full functional unit of the ISS will be set up at KIS for comparison with the behavior of the flight unit.

*Beyond 2017: During the science phase of Solar Orbiter, KIS scientists will be engaged in the scientific exploitation of the PHI data. In combinations with ground-based measurements made with GREGOR, we will have the unique possibility to carry out stereoscopic magnetic field measurement of the high solar latitudes.*

**SUNRISE**

Since the beginning of this century, KIS is strongly engaged in the SUNRISE balloon-borne observatory. SUNRISE is led by the MPS and KIS is one of the Co-Investigators.

SUNRISE is equipped with two focal-plane instruments: a tunable filter spectrometer for magnetic field measurements in the magnetically very sensitive Fe I 525.02 nm line and a filter imager for several spectral bands between 214 nm and 397 nm. KIS built the Correlation Wave-front Sensor (CWS) that provided in-flight focusing and image stabilization during the flight. The first flight of SUNRISE, with its 1m solar telescope took place in June 2009. It was a great scientific success with excellent discoveries led by KIS scientists. To date, more than 20 scientific articles with KIS participation based on SUNRISE data were published in peer-reviewed journals.

The second flight of the balloon-borne Sunrise solar observatory is scheduled for June 2013 and should have taken place shortly after this document was finished. KIS again provides an updated and improved version of the CWS and participates in the flight operation. We expect spectropolarimetric and imaging data of quiet and active Sun with extremely high quality and unprecedented spatial resolution. KIS scientists provided several observing proposals to be carried out during the 2nd flight. Thus we ensure that SUNRISE data fit to the Research Foci of KIS laid out elsewhere in this document.

Assuming a successful flight and recovery of the onboard data, KIS scientists will again be involved in the processing and the scientific analysis of these data in the years following the flight.

*Beyond 2017: With the experience gained from SUNRISE and Solar Orbiter, KIS is in the position to participate as Co-investigator in and continue making hardware contributions to future solar space (or balloon-borne) missions.*
Operation and Services

Provide contemporary access to premier solar observing facilities

KIS is leading the operation of the German solar telescopes GREGOR and VTT on Tenerife, together with national and international partners. The VTT is still the work horse for solar physicists in Germany and other European countries. Soon, this role will be assumed by GREGOR, Europe’s largest solar telescope, which is presently entering its operational phase and becoming a mature solar telescope with advanced adaptive optics, imaging and spectropolarimetric capabilities. In the not so distant future (but still outside the scope of this Research Plan), KIS will have premier access to the (then) world largest solar telescope, the Advanced Technology Solar Telescope (ATST). The ATST is presently under construction at the Hawaiian island Maui.

To make solar observations more efficient in terms of cost and time, the world’s premier ground-based telescopes will most probably offer less time to classical observing campaigns where week-long intervals are granted to a Principal Investigator (P.I.) who has exclusive use of the telescope. Instead, telescope operation in the future will concentrate on service mode observations, similar to large night-time facilities or space missions, where the telescope use is optimized by queuing observations according to, e.g., the prevailing seeing conditions.

Remote access of the P.I. to the telescope’s and visualization tools, together with the possibility to influence target selection and to modify or adapt other parameters in near real time will be an important complement of such service mode observations. Limited interactive remote access will distinguish ground-based telescopes from space-borne instruments, which offer little or no flexibility once the observing run has been scheduled. Such remote operation capability will be provided by a Center for Remote Operations (CRO), based at KIS. Within the scope of this document, the CRO will support GREGOR operations, and, to a lesser extent, suitable programs at the VTT. At the same time, experience will be gained to optimize the center for future access to the ATST. First and important steps towards a CRO are presently being undertaken in the framework of the ongoing CASSDA program at KIS, funded by the Senatsausschuss Wissenschaft of the Leibniz Association until 2015.

The CRO will provide scientists (both from KIS and from outside) with qualified technical support for the respective telescope and its instrumentation, suitable data reduction pipelines and initial analysis tools. In addition to the remote interface to the telescope, the center will dispose of suitable computer facilities for data handling and for scientific analysis. External scientists observing at GREGOR and other telescopes via the CRO will foster scientific exchange with KIS staff during their stay. Thus, the KIS will have multiple benefits from such a center:

- Efficient access to first-class solar telescopes for all staff, including students,
- Full exploitation of telescope resources,
- Scientific interaction and exchange with external scientists who use the center.

Beyond 2017: As soon as the ATST goes online, the center will also provide access to that telescope and its instruments. The EST and possibly other solar telescopes around the world can be added in due time.

Foster European efforts to build EST

KIS is a founding member of the European Association for Solar Telescopes (EAST), which is established to ensure access of European solar astronomers to world-class high-resolution ground-based observing facilities. To foster the European efforts towards the European Solar Telescope (EST), EAST initiated a Research Infrastructure in the EU 7th Framework Program on “High Resolution Solar Physics Network” (SOLARNET, 2013). KIS is the second largest partner among other 32 and plays a leading role within SOLARNET. The network will set the grounds to realize EST. EST, will - in the best case scenario - be operational by 2022. KIS plans to continue to play a major role in EAST and SOLARNET, and should be prepared to deliver a VTF-like instrument to EST. Funding of the instrument should be secured together with the telescope funding.
Cooperate with the University of Freiburg and other universities in astrophysics teaching

KIS offers an astrophysics curriculum at the Faculty for Mathematics and Physics of the Albert-Ludwigs-Universität Freiburg. The joint appointment of the director and the deputy director as professors for astrophysics at the University of Freiburg has significantly strengthened the cooperation between the two institutions. Introductory Astrophysics is an elective subject for the physics bachelor degree and is offered in the form of an introductory course (“Einführung in die Astrophysik”, 3V + 2Ü, 7 ECTS) during the summer semester for students in the fourth semester and above and a course “Theoretical Astrophysics” (2V + 2Ü, 5 ECTS) during the winter semester for students in the fifth semester and above. The exercises are organized by graduate students at KIS, in agreement with the faculty.

A curriculum for master students is under development, based on available capacity of members of the scientific staff of the institute to provide lectures covering a broad area of stellar astronomy and astrophysics, astrophysics and data management. The institute is working on a collaboration with the Observatoire de Strasbourg for the education of physics master students in astrophysics in order to extend the lectures to galactic and extragalactic as well as high-energy astrophysics and data management. This collaboration makes use of the EUCOR collaboration in the upper Rhine valley combining French, Swiss and German universities. The goal is to offer a comprehensive set of lectures in astrophysics to physics master students as elective subjects. There is no intent (and no capacity) to offer a separate astrophysics master curriculum. Graduate students participate in the general teaching activities of the Physics Institute of the University of Freiburg according to an agreement of KIS with the University.

The Schauinsland Observatory of the KIS near Freiburg offers the opportunity to bachelor and master students to have practical training during the summer semester. The observatory has recently been upgraded with a 35 cm Maksutov telescope for stellar photometry to add stellar observations to the already existing solar spectropolarimetric measurements. Student seminars with topics on astrophysics and heliospheric physics are offered at the institute during the winter semester.

In addition to the curriculum, the institute offers paid research trainee positions for periods of 6 to 8 weeks. During this time, students participate in the research work in one of the foci or in technical development under supervision of a staff member. This program is targeted at bachelor and master students to give them an opportunity for first-hand research experience, similar to summer studentships elsewhere. It also serves to attract students to do their theses at the KIS.

In addition to the directors, two scientists acquired the right for independent teaching (habilitation) at the University of Freiburg (W. Schmidt in 2001 and M. Roth in 2013). It is expected that more junior scientists will aspire to receive habilitation in order to further their careers, with the support of the institute, during the period covered by this plan. Employees of KIS are regularly invited to international summer schools, aimed at giving students a closer insight into solar research.

The involvement of the institute in academic teaching has resulted in a proliferation of internationally successful solar researchers. Several former alumni of the institute have returned to KIS after successful international careers. These efforts will continue throughout the period covered by this plan.

Offer exciting projects for Master and PhD students

KIS offers numerous cutting-edge research projects in solar and astrophysics to Master and PhD students. On the one hand, students have a state-of-the-art computer infrastructure at their disposal. On the other hand, they also greatly benefit from the institute’s leading position in operating the telescopes on Tenerife as well as KIS’s significant contribution to international projects in the field of solar physics.

In their realization of innovative projects in both theoretical and experimental astrophysics, students are furthermore assisted on a daily basis by a team of experienced scientists. In addition, KIS staff contributes to the education of undergraduates by teaching astrophysics classes at the University of Freiburg, which has proven to be an efficient means of recruiting young researchers.

While opportunities of third-party funding are successfully exploited wherever this is possible, graduate students can furthermore rely on funding by the institute during the startup phase of their research project. By
this procedure, KIS ensures the steady influx of young, high-profile candidates, who are attracted to the institute both by its research facilities and staff as well as by the career opportunities that it offers.

**Share scientific knowledge with the general public**

KIS is fully aware of its responsibility to share knowledge with the public. We regularly post new results on our web site, collaborate with the press to communicate important findings in accessible ways, present public talks, give interviews on TV and radio stations and the internet, and answer inquiries by journalists and private persons.

An ideal location for public relations work is our observatory on the Schauinsland near Freiburg, where we can demonstrate the functioning of a solar telescope and take advantage of a lecture hall to explain new results in solar physics. This is regularly done on “open house” Sundays, which we offer once per month during the summer, but also on many other occasions (upon special arrangement) for visitor groups ranging from schools to students from other faculties, from hiking groups to amateur astronomers and to researchers from various fields. Overall, 1100 – 1600 people visited the observatory per year over the last few years. Additional visitors are hosted at the main institute in Freiburg (in particular during the winter) and at the observatory on Tenerife.

Among the natural sciences, solar physics and astronomy in general have great potential to catch the interest of the public and thus to guide young people into studying science and engineering. Therefore we consider it essential to work with school students at all levels in various forms, from short observatory tours to full-day exercises at the telescope, up to one-week stays at the institute, where the students have the opportunity to learn about scientific methods in order to help them decide if research might be one of their goals in life. We also organize every year a seminar where we inform teachers about our newest findings.

The Kiepenheuer Institute is committed to maintain this level of public relations work in the future, in order to return the investment of society in our research.