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Prospects of Solar Physics from the Ground

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Abstract. The solar magnetism, its origin, and its impact on the earth are of primary interest for solar physicists. The understanding of the solar dynamo in the convection zone and the coupling of the magnetic fields up to the corona and the heliosphere calls for synoptic as well as for high spatial resolution observations of the Sun. Understanding the interactions between radiative and magneto-convective processes at the interface between the solar interior and the atmosphere requires spectro-polarimetric observations at high spatial and spectral resolution with high polarimetric accuracy. Thus large-aperture telescopes are needed to resolve the small scales and to collect enough photons to study the evolution of the magnetic processes. For assembling the mosaic of the solar dynamo and its magnetic coupling out to the heliosphere, large scale properties and hence synoptic observations play a crucial role. I present my personal perspective of the prospects in ground-based solar physics, and comment on the planned and upcoming new facilities including SOLIS, GREGOR, NST, SUNRISE, and ATST, as well as ALMA and FASR, but also mention the upcoming space missions HMI@SDO and SOLAR-B.

Keywords. Sun: activity, Sun: magnetic fields

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1. Scientific background

Advances in observational solar physics are nowadays based on (1) high spatial resolution observation to understand the physics on the small scales, and (2) full-disk observations to understand the connectivity to the large scales. Such data can then be compared with theoretical predictions. Theoretical predictions are based on (1) ab-initio simulations of the small scales and on (2) models for the larger scales in which the physical effects are parametrized. The challenge consists of designing models with which one can understand the small scales and their relation to the large scales. The small scales are self-organized and produce a coherent large scale effect, which is manifested by the solar cycle.

The Sun serves as an laboratory to study astrophysical processes on small scales in order to understand their interactions to generate large scale phenomena. The scientific objectives for driving future efforts in solar physics may be summarized by: (a) Global and long term properties: Internal structure, dynamo, evolution of surface magnetic fields. (b) Photosphere: Radiative magneto-convection. (c) Chromosphere: Non-linear magneto-acoustic gravity waves and non-LTE radiative transport. (d) Corona: Transport and dissipation of energy. Above those topics is the quest for understanding the magnetic coupling between different layers, from the solar interior to the heliosphere: (i) The loss of magnetic helicity by coronal mass ejections in the corona may be crucial for the operation of $\alpha\omega$-dynamos in the deep convection zone. (ii) The details of flux emergence from the convection zone to the corona needs to be understood, and progress in this field has been presented at this meeting by F. Moreno Insertis and V. Archontis. (iii) The braiding of magnetic field lines which is a likely mechanism how motions at the photospheric level cause reconnection and heat dissipation in the corona.

Today, more than 100 solar observatories exist all around the world (cf. a list compiled by K. Reardon: http://www.arcetri.astro.it/~kreardon/EGSO/gbo/), but only a few of them are equipped with an adaptive optics (AO) system to provide high spatial resolution. AO systems are in operation at the German VTT in Tenerife, the Swedish SST on La Palma, and the U.S.American DST of NSO at Sac Peak and is under development at Big Bear Solar Observatory (BBSO). Also the French THEMIS plans to install an adaptive optics system by 2007.

2. Internal structure: the dynamo

From full disk investigations we learn that the magnetic field is organized coherently on global scales, best demonstrated by the butterfly diagram and Hale's polarity rules. One of the greatest challenge of solar physics is understanding the physics by which this diagram is produced. As the solar cycle period is some 11 years, we need long-term measurements of the full disk solar magnetic fields. Up to now we can only rely on data from images and dopplergrams to measure solar oscillations and simple magnetograms which are used as a proxy for the large-scale magnetic fields.

With global and local helioseismology we learn about the structure and the differential rotation of the interior. With MDI@SOHO and GONG data, impressive advances were made during the last ten years, as e.g., the map of rotation of the solar interior, or the time variability of differential rotation (torsional rotation). For further progress in helioseismology new methods for the description of wave propagation need to be developed, accompanied by new and more sophisticated instrumentation.

2.1. *HMI@SDO*

The Helioseismic and Magnetic Imager (HMI) onboard the Solar Dynamic Observatory (SDO), which will be launched in 2008, will take full-disk images in 4 Stokes parameters at a spatial resolution of $1''$, and a cadence of 90 s. These filtergrams with a FWHM of 8.4 pm will be taken at 5 wavelength positions with a spacing of 7.5 pm scanning the nickel line at 676.8 nm which has $g = 1.5$. Helioseismology with HMI will be complemented by a continuation of GONG, to calibrate and confirm HMI results. Although the HMI instrument has a high time cadence and a high spatial resolution, well suited for helioseismology and for studies of the evolution of active regions as it measures the full Stokes vector, its spectral resolution is quite poor.

2.2. *SOLIS*

HMI will be complemented by the Synoptical Optical Long term Investigation of the Sun (SOLIS) with a much better spectral and polarimetric resolution, which is needed to understand the details of the atmospheric structure. SOLIS at the Kitt Peak Vacuum telescope will deliver long term full disk observations of 4 Stokes parameters with a high spectral resolution ($\geqslant 200\,000$) and sufficient polarimetric accuracy. Such a data set will be available for the first time. The measurement of all Stokes parameters is essential to properly calibrate for the polarimetric cross-talk of the instrument and the telescope (e.g., Beck *et al.* 2005). Only then, reliable quantitative measurements for inferring the magnetic field and the atmospheric structure can be obtained.

HMI and SOLIS will give important contribution for studying the properties of the solar cycle: (i) The cycle dependence of sunspot properties, like the central magnetic field strength, the central temperature, and their total magnetic fluxes. Such potential variations may give new clues to understand the generation of the cycle. (ii) The measurement of poleward transportation of magnetic flux may provide input for dynamo models that are based on flux transport. (iii) The annihilation of magnetic flux and the evolution of active regions, including the formation and decay of sunspots may give new insights into the magnetic coupling from the interior to the outer atmosphere. In this context, SOLAR B, which will be launched in September 2006, and which carries a full Stokes spectrograph together with a 50 cm aperture telescope, will deliver significant insights. (iv) From helioseismology we expect new results on the dynamics of the convection zone and the tachocline.

As pointed out by A. Ruzmaikin at the conference, the entropy gradient that drives the meridional circulation would be a quantity of great interest. The associated temperature gradient would give independent and direct information about the surface flows. However, this task is very challenging since full disk temperature maps would need to be measured with an accuracy of significantly less than 1 K. This seems not possible with any of the upcoming telescopes or missions.

3. Solar surface at small scales: radiative magneto-convection

The fascinating and complex evolution of the small scales and their inherent dynamics is illustrated by recent observations at the 1 meter Swedish Solar Telescope by Rouppe van der Voort *et al.* (2005). A movie of G-Band images of an active region containing small pores and a large number of G-Band bright points, reveal that bright points evolve on smaller time scales than granules, seemingly being pushed around by granular flows, thereby changing their form of appearance continuously. As these intergranular bright points are associated with magnetic fields, the field properties change continuously. Indeed, such observations and recent magneto-convective simulations (Vögler *et al.* 2005, Schaffenberger *et al.* 2006, Stein & Nordlund 2006) suggest that the magnetic field lines which constitutes a bright point is not a static configuration, but highly dynamic, and the spatial scale is as small as $0.05''$.

This settles a long standing problem of how magnetic flux tubes can exist, since they are unstable against interchange instability. Theoreticians have proposed that a whirl flow might be present which could stabilize them (Schüssler 1984). Such a whirl flow has so far not been detected! Well, considering the results from Rouppe van der Voort *et al.*, it seems that a whirl flow is not needed, since flux tubes are not stable, but highly dynamic. Processes such as advection by the granular flow and the convective collapse, which increases the concentration of the magnetic field, are counteracted by all sorts of MHD instabilities which disperse the magnetic flux. New simulations of magneto-convection including sophisticated radiative transport treatments should in the near-by future give more insight into the relevant physical effects and interactions. These new insights are of great consequence for understanding the evolution of magnetic fields in general, and for understanding the global sun including the internal structure, the outer atmosphere and the solar dynamo.

The example of the interchange instability demonstrates nicely that an increase in aperture from 50 to 100 cm leads to a significant increase in physical understanding of the small scales, and that the small scales are essential to understand the large scales. Having said this, it is important to note that we are far from fully understanding the small scales.

Another prominent small-scale phenomenon is the fine structure of sunspot penumbrae: The penumbral magnetic and velocity fields are known to exhibit a complex topology. Today it is commonly assumed that the penumbral magnetic fields are uncombed, i.e. that horizontal and inclined field lines are interlaced. This has crucial consequences for the interpretation of the measurements: Two or more magnetic components may be present

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along the line of sight or in the resolution element. This is certainly true in sunspot penumbrae, but may also be true for small-scale magnetic elements.

3.1. *The case for multi-line spectro-polarimetry*

The above mentioned SST observations give proxies for the magnetic field in terms of G-band brightness, but they do neither measure the magnetic field nor the inherent flow field. It should be repeated here that the magnetic field can not be measured directly, but that it must be inferred by interpreting the line profiles of the Stokes parameters, and that the inference is not straight forward, as the solutions are not unique. In order to reduce the ambiguity, the amount of information needs to be increased by performing multi-line spectro-polarimetry of all 4 Stokes parameters with high spectral and polarimetric resolution.

It is of great advantage to perform simultaneous measurements in different wavelength regimes, because: (i) The measurement of the magnetic field strength is most reliable in the strong-field regime of the Zeeman effect (full splitting). Whether or not this is the case depends on the wavelength and magnetic sensitivity of a line: the splitting is $\propto \lambda^2$, while the Doppler broadening is $\propto \lambda$. In the weak field limit only the magnetic flux can be determined, as the inferred magnetic field strength depends on the filling factor α, which is unknown as long as the structure is not spatially resolved. (ii) In the weak field limit, the measurements are more sensitive to magnetic flux and smaller signals (magnetic fluxes) can be detected more easily than in the strong field limit. (iii) Also the magneto-optical effect depends on wavelength and can be used as a diagnostic tool, e.g. in disentangling the complex field topology in penumbrae (Müller *et al.* 2002). (iv) If the lines form in different heights, information about the stratification can be gained.

In order to retrieve the properties of the atmosphere, like the thermal stratification, the magnetic field, and the velocity field, it is therefore necessary, though not necessarily sufficient, to perform co-spatial and co-temporal multi-line spectro-polarimetric measurements in different wavelength regimes. Such multi-line measurements are possible with THEMIS, DST, and the VTT. At the VTT two spectropolarimeters are operated simultaneously: the Tenerife Infrared Polarimeter (TIP) for near-infrared wavelengths, and the POlarimetric LIttrow Spectrograph (POLIS) for lines at 630 nm and 396 m. Of course, such multi-line measurements can also be achieved by combining several telescopes.

3.2. *Adaptive optics and image reconstruction*

All spectroscopic and spectro-polarimetric measurements today are limited by the photon flux. To collect enough photons for a decent signal to noise ratio, exposure times that are significantly longer than the time scale of the seeing are needed. Spectra with a spatial resolution close to the diffraction limit can only be obtained if the seeing, i.e. the wavefront, is stabilized during the exposures. This calls for adaptive optics (AO)!

To characterize the seeing quality of a telescope site, the Fried parameter, r_0, is commonly used. It corresponds to the maximum aperture which would produce diffraction limited images. For the best sites, Fried parameter up to 15 cm@430 nm are possible. Any telescope aperture larger than the Fried parameter does not improve the image quality. However, if individual images are taken with exposure times of about 10 ms (seeing time scale), several techniques (speckle, phase diversity, blind deconvolution) exist to reconstruct the wavefront and to produce diffraction limited images. Yet, if the exposure times are larger than the seeing time scales as it must be the case for sophisticated spectro-polarimetric measurements, the wavefront needs to stabilized by an AO system.

The Fried parameter depends on the wavelength: $r_0 \propto \lambda^{6/5}$, i.e., 15 cm@430 nm correspond to 70 cm@1565 nm. As an example, consider a measurement at 1565 nm with

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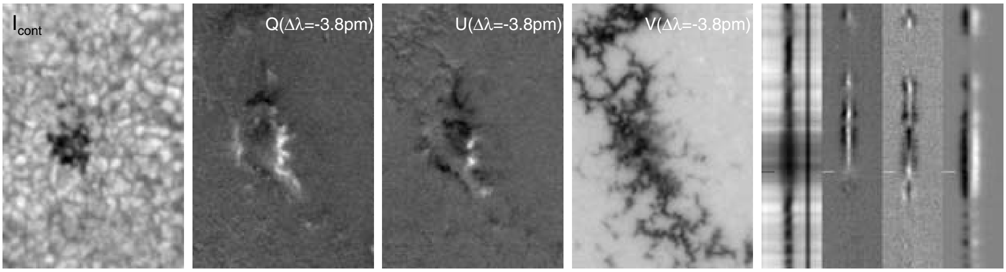

Figure 1. First light data from the imaging spectropolarimeter VIP@TESOS, which uses three Fabry-Pero-Interferometers to scan through Fe I 630.2 nm at a spectral resolution of 200 000 with 50 wavelength points across the line profile. As the total exposure time amounts to 90 s in order to obtain a polarimetric accuracy of 10^{-2} in intensity, a stable AO system is crucial for the quality of such data sets. The images display from left to right filtergrams of the continuum intensity, Stokes Q, U, and V at -3.8 pm from the line core, and a constructed spectrum for the 4 Stokes parameters (Bellot Rubio, Kentischer, Tritschler, & Beck 2006).

TIP@VTT (aperture of 70 cm). For long exposures ($\gg$ 10 ms), a low order AO system (KAOS: Kiepenheuer Adaptive Optics System) suffices to produce diffraction limited spectro-polarimetric maps ($\approx 0.6''$) and is essential for long exposure measurements as demonstrated in Fig. 1. The low order AO system uses a relative small number of lenslets (KAOS has 36) in the wavefront sensor and actuators (KAOS has 35) in the deformable mirrors. In order to successfully correct for smaller wavelength (corresponding to smaller r_0) or for larger apertures a high order AO is needed (a high order system becomes low order for larger apertures)! To date, the only working high order AO system is installed at the DST. The success of next generation telescopes like GREGOR, NST at BBSO, and ATST will crucially depend on the performance of their AO systems. Existing large aperture telescopes like the SST plan to upgrade their AO system to higher orders.

So far we have only considered the Fried parameter, which is defined for a specified loaction on the solar surface, the 'lock point', e.g., a granule. A regular AO system performs best at lock point, but degrades significantly with distance from the lock point. The corrected area (patch) is described by the iso-planatic angle, which determines the field of view which is properly corrected by the AO system. The deformable mirror is focussed to the entrance pupil of the telescope to correct the wavefront which is distorted by the local turbulence. Typically there is a second layer of turbulence in some 10 km height, which limits the isoplanatic patch. With the help of a second deformable mirror focussing on that layer, the iso-planatic angle can be increase substantially. The use of two or more deformable mirrors is called multi-conjugated adaptive optics (MCAO). For technical reasons, two wavefront sensor are commonly used instead of one. It was demonstrated recently at the VTT for the first time that MCAO works by proving that it substantially increased the corrected field of view (v. d. Lühe, Berkefeld, & Soltau 2005).

With the success of low and high order AO, and with MCAO, the preconditions of designing and building large-aperture ground-based telescopes are fulfilled.

3.3. *Upcoming high resolution optical ground-based telescopes*

To advance in solar physics, we need large aperture telescopes. The fundamental length scales like pressure scale height and mean photon free path correspond to $0.1''$. MHD simulation even predict smaller structure elements of about $0.05''$. In addition to the diffraction limit, time resolution and polarimetric accuracy demand for large apertures. One needs to keep in mind that "the number of photons per wavelength per second per (diffraction limited) resolution element is independent of aperture size". Ground based telescopes are much cheaper than going into space: What can be done from the ground should be done from the ground. And the advances in overcoming the seeing make it possible to build large aperture telescopes on ground. In this section I will give a short list of upcoming solar observatories which are devoted to high spatial resolution.

3.3.1. *GREGOR at OT (1.5 m)*

GREGOR at the observatory de Tenerife (OT) is a joint project of three German institutes, the Kiepenheuer-Institut für Sonnenphysik in Freiburg (KIS), the Institut für Astrophysik in Göttingen (IAG), and the Astrophysikalische Institut in Potsdam (IAP), and it will have post-focus instrumentation contributions from the Spanish Instituto de Astrofísica de Canarias (IAC). The aperture amounts to 1.5 m. The telescope is on-axis, i.e., polarization-free until the light is fed into a Coudé-beam and is mounted on an alt-azimuth structure. The mirrors are made of Cesic (Silicon Carbide), which has the advantage of a very high heat conductivity, such that an active cooling on the backside of the mirror can keep the mirror temperature at the ambient air temperature within $\pm$ 0.2° C. The first light is planned for the end of 2006. The field of view amounts to 300$''$, and the telescope is designed for a wavelength range of 0.39 μm – 5 μm.

3.3.2. *NST at BBSO (1.6 m)*

The New Solar Telescope (NST) is a project of the New Jersey Institut of Technology (NJIT), which operates the Big Bear Solar Observatory (BBSO). The NST has an aperture of 1.6 m, and an off-axis design to reduce the straylight in order to allow for corona observations. The primary mirror is made out of Zerodur and is actively cooled to suppress mirror seeing. The field of view is 180$''$ and the planned wavelength range is 0.35 μm – 1.6 μm. First light is scheduled for 2008.

3.3.3. *SUNRISE (1m)*

SUNRISE is a German, U. S. American, and Spanish project which is led by the Max-Planck-Institut for Solar System Research (MPS). It is a balloon-borne telescope which will fly in an elevation of 40 km in 2009. It has an aperture of 1 m and an on-axis design. The wavelength range is specified to be 220 nm – 700 nm. At 220 nm it is designed to reach a spatial resolution of 0.05$''$! It is equipped with a polarimetric spectrograph (SUPOS), a polarimetric filtergraph in the Visible (IMAX), and a filtergraph for UV and Visible wavelengths (SUFI).

3.3.4. *ATST (4 m)*

The Advanced Technology Solar Telescope (ATST) with a planned aperture of 4 m is the most important project for the future of Solar Physics. It is an U. S. American project led by NSO. After a site testing campaign, Haleakala (Hawaii) was selected. Its off-axis design allows for corona observations, and is of advantage for AO systems and observations in the infrared. The field of view is 300$''$, and 300 nm – 35 μm is the specified wavelength range. It is aimed to have a polarimetric accuracy of 10^{-4} in intensity. There are plans for international contributions, e.g., instruments.

4. Exploring the magnetic fields of the outer atmosphere

This contribution does not focus on the outer atmosphere as measurements of magnetic fields in the chromosphere and the corona are nicely reviewed by A. Lagg in this volume. In the infrared and the visible, the Zeeman and Hanle effects are used, while

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gyroresonance emission and Faraday rotation is used for radio wavelenghts. The actual measurement of magnetic fields in the outer atmosphere is of great importance for validating the large number of models and theories that exist. For the infrared and visible wavelenghts, large aperture off-axis telescopes are necessary, which do not suffer from straylight. For completeness, I mention that the continuum in the mm-range forms in the chromosphere, such that ALMA (Atacamar Large Millimeter Array) will provide new insight, while the cm-range forms in the corona, for which FASR (Frequency Agile Solar Radiotelescope) is best suited.

5. Summary

Solar Physics is a vivid field of research. Elementary astrophysical processes can be studied on the Sun. The great challenge of future research is to understand the small scales, and how they interact to generate the large scale phenomena, which are characterized by long term coherence, as manifested by the butterfly diagram. Only then, it will be possible to describe the magnetic coupling from the solar interior to the heliosphere, which has many and important implications on our life on earth.

Further advances call for long term observations of the full disk with GONG, HMI@SDO and SOLIS, inferring the magnetic field and the velocity field of active regions and of bulk motions in the convection zone on the one hand, and on the other hand, we need spectropolarimetric measurements at highest possible spatial resolution, together with sufficient spectral, polarimetric, and temporal resolution. To reach this goal we need large aperture telescopes which are equipped with sophisticated adaptive optics systems (multi conjugated adaptive optics). Such AO systems will be complemented with image reconstruction techniques, like, e.g., speckle, phase diversity, and blind deconvolution. Such telescopes need to have multi-line spectropolarimetric capabilities, in order to reliably reconstruct the field topologies and the atmospheric stratification. The upcoming facilities like GREGOR, NST, SUNRISE, from ground, and SOLAR-B will contribute. Future facilities like, most importantly, ATST for optical wavelengths, as well as ALMA and FASR for radio wavelengths will deliver fascinating new science and will set the grounds for major advances in the field of solar astrophysics.

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