SOLAR MAGNETIC PHENOMENA
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Proceedings of the 3rd Summerschool and Workshop held at the Solar Observatory Kanzelhöhe, Kärnten, Austria, August 25 - September 5, 2003

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# Table of Contents

*Preface*  ix  

**Invited Lectures**

Observations of Photosphere and Chromosphere  
* C. Denker  1  

Solar Flares – Observations and Theory  
* B. Vršnak  27  

Coronal Mass Ejections and Magnetic Helicity  
* L. van Driel-Gesztelyi  57  

High Energy Radiation from the Sun  
* J.C. Brown  87  

Physics of Solar Prominences  
* P. Heinzel and U. Anzer  115  

Eight Years of SOHO: Some Highlights  
* B. Fleck  139  

**Contributed Papers**

2D Compressible Reconnection Model  
* M. Skender and B. Vršnak  167  

Waiting Time Distribution of CMEs  
* C.-T. Yeh, M.D. Ding and P.F. Chen  171  

Simultaneous Visible and IR Spectropolarimetry of the Quiet Sun  
* I. Domínguez Cerdeña, J. Sánchez Almeida and F. Kneer  175  

A Simple Topological Model of the Bastille Day Flare (July 14, 2000)  
* I.V. Oreshina and B.V. Somov  179  

Spectropolarimetry in a Sunspot Penumbra at High Spatial Resolution  
* N. Bello González, O. Okunev and F. Kneer  183  

X-Ray and Hα Emission of the 20 Aug 2002 Flare  
* J. Kašparová, M. Karlický, R.A. Schwartz and B.R. Dennis  187
Center-to-Limb Variation of Facular Contrast Derived from MLSO RISE/PSPT Full Disk Images

F.L. Vogler, P.N. Brandt, W. Otruba
and A. Hanslmeier

The Acceleration-Velocity Relationship in 5000 LASCO-CME’s

D. Ruždjak, B. Vršnak and D. Sudar

Time Evolution of the Spectral Index in Solar Flares

P.C. Grigis, D. Buser and A.O. Benz

Analysis of Doppler Shifts of Spectral Lines Obtained by the CDS/SOHO Instrument

P. Gömöry, J. Rybáč, A. Küčera, W. Curdt and H. Wöhl

On the Behaviour of a Blinker in Chromospheric and Transition Region Layers

F. Tomasz, J. Rybáč, A. Küčera, W. Curdt and H. Wöhl

On the 24- and 155-Day Periodicity Observed in Solar Hα Flares

M. Temmer, A. Veronig and A. Hanslmeier

He-D<sub>3</sub> Polarization Observed in Prominences

R. Ramelli and M. Bianda

Line-of-Sight Velocity and Magnetic Field in Sunspot Penumbrae

D.V. Makarchik and N.I. Kobanov

Impulsive X-Ray Radiation Characteristics of Solar Flare Footpoints

T. Mrozek and M. Tomczak

Velocity Fields in an Irregular Sunspot

J. Jurčák, M. Sobotka and V. Martínez-Pillet

On the Dynamic Disconnection of Rising Ω-Loops

L. Tóth and O. Gertel

Searching for the Origins of the Fast Solar Wind

M.D. Popescu and J.G. Doyle

Detectability of High Frequency Acoustic Waves with TRACE

A. Fossum and M. Carlsson
Linking Coronal to Interplanetary Magnetic Helicity
   M.L. Luoni, S. Dasso, C.H. Mandrini,
   L. van Driel-Gesztelyi and P. Démoulin 243

Debrecen Photoheliographic Data and its Comparison
   with Other Sunspot Databases
   G. Mező, T. Baranyi and L. Győri 247

Properties of a Small Active Region in the Solar Photosphere
   S. Stangl and J. Hirzberger 251

Small Scale Events Seen in SXT Observations
   S. Gburek and J. Sylwester 255

Properties of Type IV Radio Bursts with
   Periodical Fine Structures
   J. Magdalenić, B. Vršnak, P. Zlobec,
   M. Messerotti and M. Temmer 259

Testing the Neupert Effect
   A.M. Veronig, J.C. Brown, B.R. Dennis,
   R.A. Schwartz, L. Sui and A.K. Tolbert 263

The Faint Young Sun Problem
   A. Hanslmeier 267

CCD Spectroscopy of Solar Rotation
   S. Jejić and A. Čadež 271

The Observing Programs at Kanzelhöhe Solar Observatory
   W. Otruba 275

Theoretical Modeling of Potential Magnetic Field
   Distribution in the Corona
   V.M. Čadež, A. Debosscher, M. Messerotti,
   P. Zlobec, M. Iurcev and A. Santin 279

Author Index 283
Preface

The concept of summerschools and workshops at the Kanzelhöhe Solar Observatory, Kärnten, Austria, devoted to up-to-date topics in solar physics has been proven to be extremely successful, and thus in August/September 2003 the third combined summerschool and workshop was held there.

This book contains the proceedings of the Summerschool and Workshop “Solar Magnetic Phenomena” held from 25 August to 5 September 2003 at the Solar Observatory Kanzelhöhe, which belongs to the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria. The book contains the contributions from six invited lecturers. They give an overview on the following topics: observations of the photosphere and chromosphere, solar flare observations and theory, coronal mass ejections and the relevance of magnetic helicity, high-energy radiation from the Sun, the physics of solar prominences and highlights from the SOHO mission. The lectures contain about 25 to 30 pages each and provide a valuable introduction to the topics mentioned above. The comprehensive lists of references at the end of each contribution enable the interested reader to go into more detail.

The second part of the book contains contributed papers. These papers were presented and discussed in the workshop sessions during the afternoons. The sessions stimulated intensive discussions between the participants and lecturers.

On behalf of the organizing committee and all the participants, we wish to thank the following organizations and companies for their financial support: the Austrian Bundesministerium für Wissenschaft und Forschung, European Space Agency (ESA), Italian Space Agency (ASI), University of Graz, INAF-Trieste Astronomical Observatory, Marktgemeinde Treffen, Land Steiermark, Raiffeisenbank Kärnten.

Graz and Trieste, July 2004

Arnold Hanslmeier, Astrid Veronig and Mauro Messerotti
Abstract. Solar physics has seen a decade of exciting science and discoveries, which were driven by new instruments for ground- and space-based observations. Multi-wavelength observations involving many observatories now routinely cover the whole solar atmosphere from photosphere, to chromosphere, transition region, corona, and heliosphere and have become an integral part in any type of space weather forecasting. The solar photosphere and chromosphere has historically been the domain of ground-based observatories and this review will be based on observations and research projects that have been carried out at the Big Bear Solar Observatory (BBSO) to illustrate current trends and prospects for ground-based experimental solar physics.

1. Introduction

The Sun is the only star where we can observe surface structures in fine detail. Elementary magnetic flux tubes are generated by a self-excited dynamo mechanism and are embedded in convective plasma flows. A recent review of numerical simulations of solar magneto-convection has been given by Schüssler (2001) who points out that at the moment, we lack observations with adequate spatial, temporal, and spectral resolution to validate or reject theoretical models of magneto-convection. Solar observations have to cope with the earth’s turbulent atmosphere, which is heated by solar radiation causing severe degradation of image quality – so-called “seeing”. The advance of a next generation of solar telescopes in combination with adaptive optics (AO), post-facto image reconstruction techniques, and sophisticated post-focus instrumentation, namely two-dimensional spectro-polarimetry, have brought us closer to the goal of resolving the fundamental length and time scales of solar magneto-convection.

The present review focusses on recent observations of the solar photosphere and chromosphere to illustrate the characteristic spatial distribution of highly intermittent magnetic fields in various environments, to study
the energetics related to non-thermal heating and inhibition of convective energy transport by magnetic fields, and to link the dynamics of small-scale magnetic fields to instabilities, wave excitation and propagation, and the reconnection of magnetic field lines. Ultimately, the intrinsic temporal and spatial scales of magneto-convection are related to global aspects of solar variability and therefore to basic physical processes on the Sun that affect the Earth environment, e.g., communications technology, the power grid, civil and military assets as well as humans in space, and in the end, the terrestrial climate.

Generation and dissipation of small-scale solar magnetic features are responsible for the dynamics above the photosphere. Observations of small-scale magnetic fields, with the highest resolution possible, are crucial to the understanding of mass and energy transport throughout photosphere, chromosphere, transition region, and corona. The morphology and physics of sunspots and associated phenomena is carefully illustrated in the classical text by Bray and Loughhead (1964) and the hierarchy of solar magnetic fields has been reviewed by Zwaan (1987). The size spectrum of solar magnetic fields ranges from sunspots, pores, and magnetic knots to faculae and network clusters and finally to the theoretically predicted flux fibers with dimensions of just a few tens of kilometers. A collection of research papers relating sunspot observations and theory was assembled in the monographs by Thomas and Weiss (1992) and Schmieder, del Toro Iniesta, and Vázquez (1997).

2. Quiet sun magnetic fields

In a quiet region, magnetic fields can be generally divided into two categories: network fields and intranetwork fields (IN). The observable fields are in the form of discrete magnetic elements. Network fields are found in the boundaries and, particularly, in the vertices of supergranule cells (Simon and Leighton, 1964; Wang, 1988). The intranetwork fields are mixed-polarity magnetic elements inside the network. Two important processes for the creation and destruction of magnetic elements of the quiet sun are ephemeral regions (Harvey and Martin, 1973) and “cancellation” (Livi, Wang, and Martin, 1985; Martin, Livi, and Wang, 1985). Wang et al. (1995) obtained a number of sequences of quiet sun magnetograms, where they studied the distribution of IN magnetic fluxes based on some of the best BBSO magnetograms and found a peak flux distribution at $6 \times 10^8$ Wb. However, their findings cannot directly be applied to magnetic flux in other kinds of magnetic structures, i.e., their study should be extended to many regions, including quiet network, enhanced network, and coronal holes. After all, the magnetic structure is the dominant factor in producing
microflares and mini-filament eruptions. In addition, Wang et al. (1996) applied local correlation tracking (LCT) to long-integration magnetograms and confirmed that IN fields follow supergranular flows and are swept to the network boundary. But they do not contribute to the formation of network fields because of their bipolar nature. Furthermore, the interaction between network and IN fields, can produce at least $1.2 \times 10^{21}$ J s$^{-1}$ of energy, which is comparable to the energy required for coronal heating.

3. Spicules, macrospicules, and surges

It is now widely accepted that magnetic fields play a fundamental role in defining the structure, mass, and energy flows in the chromosphere and corona (Withbroe and Noyes, 1977). Nevertheless, we are still some distance away from a satisfactory understanding of the detailed mechanisms of energy and mass transport in the sun, mainly because of our limited knowledge of the various kinds of small-scale dynamic structures, which are thought to be important in mass and energy transport. Spicules are common chromospheric phenomena and their appearance led to the figurative expression “burning prairie” to describe the chromosphere. They are predominantly located near the chromospheric network where the magnetic field is moderate and small-scale magnetic elements are concentrated. Spicules are less likely to occur near active regions where the magnetic field is much stronger. In polar regions and in coronal holes, spicules are more elongated and almost normal to the surface. The direction of their trajectories is preferentially along local magnetic lines of force. The upward mass flux in spicules is about 100 times that of the solar wind and has to be considered for the mass balance of the solar atmosphere. The velocities in spicules are in the order of the sound and Alfvén speed of the photosphere and chromosphere. Athay (2000) suggests that spicules are an integral part of the dynamic interaction between the chromosphere and the corona and that these dynamics are driven by the heating rates of spicules, which leads to the question: Is the chromospheric heating rate constant with height, especially in the upper layers of the chromosphere? A recent review of spicules, their observed properties and competing models is given by Sterling (2000). Figure 1 shows a typical BBSO Hα full disk image, which image has been corrected by a Kuhn-Lin style flat-field image (Kuhn, Lin, and Loranz, 1991) and a limb darkening profile was subtracted to enhance the contrast of disk and limb features (Denker et al., 1998).

Johannesson and Zirin (1996) measured the height of the solar chromosphere from high resolution Hα filtergrams during the solar minimum period in 1994 and 1995. They determined the frequency of macrospicules as a function of azimuth. The chromospheric height is about 4,300 to
4,400 km at the equator and increases to just below 6,000 km at the poles. The height of the chromosphere increases locally above active regions. Macrospicules can be detected as elongated features extending radially outward with sizes of 7,000 km to 20,000 km above the limb. They are commonly confined to coronal holes near the solar poles. Typical numbers are about 20 macrospicules per 150″ along the limb. There is still some controversy over which disk features correspond to macrospicules. However, two-dimensional spectrometry of the Hα line in combination with accurate high-spatial polarimetry might just provide the necessary clues to clarify this question. Doppler shifts associated with macrospicules can exceed 50 pm, which makes it difficult to observe them at a single line position with Lyot-type filters. Macrospicules are therefore ideal candidates for two-dimensional spectroscopy. Due to the small size of macrospicules,
many of their properties are still uncertain, e.g., if the upward, supersonic velocity profile is ballistic or constant. Another interesting question is if macrospicules are associated with flaring X-ray bright points or if these are typical for (polar) surges only (Georgakilas, Koutchmy, and Cristopoulos, 2001).

4. Mini-filaments

Mini-filament eruptions were first described in detail by Hermans and Martin (1986). Wang et al. (2000b) studied them in great detail including their lifetime, morphology, and magnetic evolution. They are different from macrospicules in the sense that mini-filament eruptions have a pre-eruption phase and lack a jet-like structure. They are likely related to magnetic reconnection. Even though mini-filament eruptions appear to be different from macrospicules, there is still some similarity, since both seem to be related to magnetic reconnection. Macrospicules, long jets following polar plumes, were discovered in Skylab He II 30.4 nm overlapogram images. Moore et al. (1977) showed that Hα macrospicules are connected to tiny Hα limb flares in ephemeral regions, and that they are associated with ultraviolet (UV) macrospicules. Based on their observations, macrospicules and microflares may be associated. Wang (1998) compared macrospicules in He II 30.4 nm and Hα and concluded that macrospicules may appear either as jet-like ejections or as loop-like eruptions near the limb. There is strong evidence that they are the result of magnetic reconnection. The loop-like eruptions, however, might have been mini-filaments eruptions rather than macrospicules. It is still an open question whether or not mini-filaments are related to microflares and coordinated observations with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) might shed light onto this problem. Mini-filaments can be used as a stepping stone to understand the more complex physics of filaments, since mini-filaments eruptions may be the small-scale analogue of filament eruptions. Therefore, an investigation of this possibility and an assessment of the role of small-scale events in mass and energy transport to the upper atmosphere of the sun is warranted to investigate the possible existence of a scaling law from mature filaments to mini-filaments. Finding the link between the evolution of magnetic fields, microflares, and mini-filament eruptions is one of the important tasks in high resolution studies of the Sun.

5. Moustaches

Moustaches are a typical phenomenon of the active chromosphere, which are observed as excess emission in the line wings of strong chromospheric
absorption lines in the vicinity of sunspots, emerging flux regions, and arch filament systems. Figure 2 shows an emerging flux region and arch filament system. The moustache phenomenon was first observed by Ellerman (1917) who called these chromospheric bright points “hydrogen bombs”. However, we prefer the expression “moustache” introduced by Severny (1956), which refers to their appearance in photographic negatives of the corresponding spectra (e.g., the Balmer lines up to H$_{10}$, Ca H and K, Na D, and Mg b, see Matres and Bruzek, 1977). In H$\alpha$, a typical moustache spectrum exhibits inconspicuous absorption at line center and a brightening in the wings with a maximum around 0.1 nm off line center. The increased line wing contrast can extend to 0.5 to 0.7 nm away from the line center. The sizes of moustaches range from 5$''$ down to the diffraction limit of today’s solar telescopes of about 0.2$''$. Their typical lifetime is about 10 to 15 min and they have a tendency to reoccur.

Denker et al. (1995) applied the speckle masking technique to H$\alpha$ line wing filtergrams and showed that the moustache contrast is as high as
1.7 times the contrast of the quiet sun background. Contrasts of small-

scale features can increase up to 2 to 3 times when the seeing transfer
function (STF) is properly taken into account and many flux tube models
still rely on contrast values obtained without seeing correction. From these
observations, they concluded that the upper limit for the size of moust-
taches of 5″ is most likely due to insufficient spatial resolution in previous
observations. At the highest resolution, they identified well defined intensity
peaks, which are pushed around by the convective motion of granules and
move along intergranular lanes with speeds of 1 to 2 km/s toward their
intersections. Denker (1997) used the two-dimensional spectropolarimeter
of the Universität-Sternwarte Göttingen (Bendlin and Volkmer, 1995) at
the Teide Observatory, Tenerife, and obtained reconstructed filtergrams
in the NaD2 line with a bandpass of just 14 pm and demonstrated that
chromospheric moustaches and photospheric filigree are co-spatial.

Nindos and Zirin (1998) studied moustaches in the neighborhood of
a sunspot in a mature active region. One third of the moustaches were
associated with moving magnetic features (MMFs), whereas the remainder
were not associated with enhanced magnetic field elements. Moustaches
associated with MMFs exhibited similar proper motions of up to 1.1 km/s,
whereas the other remained stationary. Both types of moustaches were
indistinguishable with regard to lifetime, shape, dimensions, contrasts, and
temporal evolution. The observed moustaches were not circular in shape
but had an aspect ratio of about 1 1/2. Qiu et al. (2000) found another
classification where moustaches with strong chromospheric Hα emission are
well correlated with ultra-violet (UV) brightenings at atmospheric heights
corresponding to the temperature minimum and moustaches with weak
Hα emission are uncorrelated. The majority of weak moustaches is located
near magnetic inversion lines whereas strong moustaches are located at the
boundary of unipolar magnetic regions or near magnetic inversion lines. Qiu
et al. concluded that the heating mechanism of moustaches is located in
very deep atmospheric layers but that this might differ for different classes
of moustaches.

6. Penumbra formation and Evershed effect

Many still-open questions are related to the abrupt transition from nearly
vertical fields in pores to the strongly inclined fields in sunspot penum-
brae: How does the sudden topology change of the magnetic flux fibers
affect the magnetic field in transition region and corona? What effect has
the clustering tendency of emerging small-scale flux elements in active
regions on the formation of (rudimentary) penumbrae? Is the sea-serpent-

like structure attributed to penumbral filaments responsible for small-scale
chromospheric heating as observed in moustaches? These questions are drivers for observations of penumbra formation with increased magnetic sensitivity, improved spectral resolving power, and appropriate temporal resolution at sub-arcsecond spatial scales. The real-time image reconstruction (RTIR) system at BBSO (Denker, Yang, and Wang, 2001) has been designed to obtain images with a spatial resolution close to the diffraction limit of the 65 cm vacuum telescope. The disk passage of solar active region NOAA 10375 is depicted in Figures 3 and 4.

What are the essential features that distinguishes a sunspot from a pore? Pores can have diameters of up to 10″, whereas the smallest sunspots have diameters down to 5″. Rucklidge, Schmidt, and Weiss (1995) developed a simplified model of the energy transport in sunspots and pores, which describes the transition from pores to sunspots as a function of the magnetic flux Φ and the radius R of the sunspot/pore. Sunspots and pores are located on a hysteresis curve in the Φ, R-plane, and sunspots emerge from

Figure 3. Speckle reconstruction of active region NOAA 10375 on 2003 June 10 at 19:58 UT.
the pore branch at a subcritical (with respect to both $\Phi$ and $R$) bifurcation point. At this point, lateral heat transport increases sharply and penumbral structures appear abrupt and rapidly, and become a robust feature in the evolution of the sunspot. The generation of a filamentary penumbra, the on-set of the Evershed flow, and the change of the magnetic field topology take place in less than 20 to 30 min (see Leka and Skumanich, 1998), which makes penumbra formation a challenging observational task and explains why many processes of non-linear convection involved in sunspot formation are still elusive. Penumbral grains move predominantly inwards in the inner penumbra and outwards in the outer penumbra (Denker, 1998; Sobotka, Brandt, and Simon, 1999). In addition, clouds of outflows seem to migrate outwards in Dopplergrams (Shine et al., 1994; Rimmele, 1994). High resolution two-dimensional spectroscopy will enable us to resolve issues regarding the fine structure of penumbral filaments and its association with the Evershed effect, the size of the penumbral filaments and its correlation between continuum intensity, velocity, field strength and field inclination.
The abrupt formation of a penumbra and its effects on the surrounding environment should certainly affect the upper atmospheric layers. However, the exact mechanisms coupling photospheric flux tube dynamics with chromospheric activity and coronal heating are still elusive. Moustaches have been known to appear preferentially near young sunspots, where they are often concentrated at the outer boundary of the penumbra (Denker et al., 1995), especially when the penumbral filaments penetrate deeply into the granular pattern. Denker (1997, 1998) compare the appearance of moustache near sunspot penumbras in speckle interferometric continuum and NaD₂ filtergrams. Yang et al. (2003) studied two pores, which were separated by a light-bridge. A small area of penumbral filaments formed suddenly near the light-bridge indicating an abrupt change of the local magnetic field topology from almost vertical to strongly inclined magnetic fields. Subsequently cool material, which was previously suspended in a filament, stream downward. During the downward motion of the cool material, Hα Dopplergrams revealed twisted streamlines along the filament and several well-defined Hα brightenings. The moustaches occurred near the location of the descending filament material. These moustaches resided near a magnetic inversion line and were stationary, as opposed to moustaches associated with moving magnetic features (Nindos and Zirin, 1998).

Early observations revealed that in the Evershed effect, the amount of line shift decreases with increasing formation height, while the degree of the line asymmetry increases with formation height. Maltby (1964) noted that the dependence of the Evershed effect on the formation height presents evidence that the flow lies in the deepest photospheric layers. However, studies performed by Rimmele (1994) present evidence that the Evershed effect is confined to some elevated thin loop-like structures above the continuum height over most part of the penumbra. However, these elevated thin flow channels only exist on the center-side of the penumbra, while on the limb-side penumbra no such elevated flow channels were observed. This might be due to the line-of-sight effect. Recent observations by Hirzberger and Kneer (2001) do not confirm the results of Rimmele (1994). Their observations indicate that the Evershed flow is sharply confined to the penumbra and is mostly horizontal. Vertical flows were observed at both ends of penumbral filaments (Rimmele, 1995; Stanchfield, Thomas, and Lites, 1997; Schmidt and Schlichenmaier, 2000; del Toro Iniesta, Bellot Rubio, and Collados, 2001). Up-flows in penumbral grains may be the source of the horizontal Evershed flow. The majority of studies conclude that the Evershed flow is well correlated with dark filaments in penumbrae (Shine et al., 1994; Rimmele, 1995; Stanchfield, Thomas, and Lites, 1997; Wiehr and Degenhardt, 1992; Wiehr and Degenhardt, 1994; Degenhardt and Wiehr, 1994). The correlation between the horizontal magnetic field and the dark filaments in the
OBSERVATIONS OF PHOTOSPHERE AND CHROMOSPHERE 11

penumbra is still controversial. Some authors, e.g., Degenhardt and Wiehr (1991), Schmidt et al. (1992), Title et al. (1993), Rüedi, Solanki, and Keller (1999), and Westendorp Plaza et al. (2001), found a correlation between horizontal fields and dark filaments, whereas Hofmann et al. (1994) only found correlation in the inner and Lites, Skumanich, and Scharmer (1990) only in the outer part of the penumbra. There are even more controversial observations on how the field inclination and field strength are correlated.

There are two notable models that attempt to interpret the Evershed effect. Thomas (1988) interpreted the Evershed flow as a “siphon flow” along magnetic flux tubes. If a tube forms an arch between two footpoints with different values of gas pressure (at the same geometrical level), a flow is driven from the high-pressure end to the low-pressure end. The flow velocity increases along the ascending part of the arch and reaches its sonic point at the summit. On the downstream side, it first accelerates further, but then undergoes a shock, thereby adjusting its pressure to the given end pressure. The second model, the “moving-tube model” (Schlichenmaier, Jahn, and Schmidt, 1998a, 1998b), includes time dependence and does not rely on a given pressure difference. Magnetic flux tubes emerging from the deep penumbra are able to transport heat to the penumbral photosphere. In the thin flux tube approximation, a single flux tube first rises adiabatically from the magnetopause, then, at the point where it meets the photosphere it sharply bends horizontally. At this point a high temperature is sustained by the up-flow of hot gas within the tube, which has been interpreted as the observed penumbral grains. The model also yields a horizontal pressure gradient along the tube, which drives an outward flow, as in the siphon model.

7. Sunspot umbra, umbral cores, and umbral dots

Umbral dots are easier to detect in the infrared, since the umbral contrast is diminished. Near infra-red (NIR) observations of umbral dots are rare and usually limited to continuum images (Ewell, 1992). Therefore, spectropolarimetric observations in the NIR are likely to provide deeper insight into the physics of umbral dots and the energy transfer and balance within sunspot umbrae. Theoretical models of umbral dots include non-linear oscillatory convection, non-thermal heating, and penetrative convection (García de la Rosa, 1987). However, many basic properties are still uncertain. This leads to the following questions: Do umbral dots exist throughout the umbra or are there dot free regions, i.e., umbral cores that maintain their magnetic identity, thus restricting umbral dots to their periphery? Do umbral dots play a role in the formation of light-bridges? Are peripheral umbral dots related to inward moving penumbral grains and are they distinct from
stationary central umbral dots? What is the magnetic field strength in umbral dots? Do the magnetic field strength and brightness temperatures of umbral dots depend on the sunspot geometry?

Assuming local thermal equilibrium (LTE), the continuum intensity can be converted into a brightness temperature via Planck’s law. Tritschler and Schmidt (1997) find a decrease in the brightness temperature of about 30% for central umbral dots and of 20–25% for peripheral umbral dots compared to the quiet sun, which corresponds to a decrease in temperature of 1,600 K and 1,200 to 1,400 K, respectively. They do not find a significant difference between the magnetic field of umbral dots and the surrounding umbra. In both cases, the magnetic field ranges from 0.15–0.3 T. Comparing the observed spectral profiles of umbral dots with various model profiles, Tritschler and Schmidt conclude that umbral dots are a phenomenon of the deep photosphere only visible at the umbral continuum level, i.e., umbral dots are inconspicuous at the height of formation of the FeI 630.25 nm and FeI 864.8 nm line.

In the “cluster or spaghetti model” (Parker, 1979; Choudhuri, 1986), the magnetic field of the sunspot consists of many individual flux tubes at sub-photospheric levels. The flux tubes are embedded in nearly field-free plasma and umbral dots are the manifestation of over-stable convection, i.e., hot columns of gas rise between the flux tubes and the up-flow can be sufficiently strong to penetrate the magnetic arcs formed by the individual flux tubes. Assuming the sunspot is a “single monolithic flux tube”, Knobloch and Weiss (1984) showed in a nonlinear treatment of magneto-convection that elongated convection cells of 300 km diameter and 1,500 km length contribute to the energy transport within the monolithic flux tube and umbral dots are the photospheric signature of these convection cells. Sensitive and spatially resolved magnetograms will show how uniform the magnetic field in the umbra really is and NIR continuum images allow us to identify accurately the location of umbral dots, thus providing important boundary conditions for the aforementioned models.

8. Modelling the fine structure of sunspots

Schlichenmaier (1999) demonstrated that many observed penumbral features can be reproduced by simulations. Schlichenmaier, Bruls, and Schüssler (1999) modelled the radiative cooling behavior of tubes that are substantially hotter than the surrounding photosphere and showed that the cometary tail of penumbral grains can be explained by an hot up-flow that, being channelled by a magnetic flux tube, flows essentially horizontal in the photosphere. Recent numerical results of the moving tube model reveal that a subtle balance between the centrifugal force and the magnetic
curvature force at the photospheric footpoint of the tube may be essential to understand the penumbral fine structure. For a supercritical flow speed, the centrifugal force cannot be balanced by the magnetic tension and a flow overshoots into the convectively stable photosphere. In this scenario, downflows within the penumbra can be modelled dynamically by the moving tube model (Schlichenmaier, 2003).

Spectropolarimetric investigation, observational as well as theoretical, present strong evidence that the magnetic field of the penumbra is un-combed, such that the flow is concentrated in mostly horizontal flux tubes, while the background field is more inclined with respect to the horizontal and essentially at rest. Schlichenmaier and Collados (2002) have analyzed spectropolarimetric data, acquired in Fe i 1564.8 nm \((g = 3)\) with the Tenerife Infrared Polarimeter (TIP) at the German Vacuum Tower Telescope (VTT) in Tenerife. Investigating the Stokes-V asymmetries and comparing them to synthetic lines, Schlichenmaier and Collados find that the observations are compatible with up-flow channels in the inner and horizontal flow channels in the outer penumbra, while the background is at rest. Additional support was found by comparing maps of the net circular polarization of Fe i 1564.8 nm and Fe i 630.2 nm. These maps show a different behavior for the two lines, which can be understood, if one assumes horizontal flow channels that are embedded in a background at rest (Müller et al., 2002).

Steiner et al. (1998) simulated the magneto-hydrodynamical (MHD) interaction between non-stationary convection in the solar photosphere and small-scale magnetic flux sheets, using a numerical code for two-dimensional MHD with radiative energy transfer. Dynamical phenomena were identified such as the bending and horizontal displacement of a flux sheet and the excitation and propagation of shock waves and observational signatures of these phenomena (synthetic Stokes profiles) were derived. In Grossmann-Doerth, Schüssler, and Steiner (1998) the formation of concentrated magnetic flux by convective flow is simulated. Starting from an evolved state of simulated solar granulation the evolution of an initially homogeneous, vertical magnetic field, to a field concentration with a flux density up to the thermal equipartition value is followed. Convective collapse (Parker, 1978; Spruit, 1979) with a subsequent “rebound shock” is observed of which radiation diagnostics in the continuum and in spectral lines were predicted and subsequently observed by Steiner (2000) and Grossmann-Doerth et al. (2000) investigated the problem of strongly asymmetric Stokes-V profiles and came to the conclusion that pathological Stokes profiles need not necessarily be the result of mixed polarity on very small scales but instead can be formed in the presence of a magnetic canopy. These ideas have been applied in an investigation of pores and magnetic knots by Leka and Steiner (2001). They found enhanced Stokes-V asymmetry on the periphery of pores and azimuth
Figure 5. C$\alpha$ 610.3 nm line wing image of active region NOAA 10375 obtained with the DVMG system at the 25 cm vacuum refractor on 2003 June 10. The longitudinal magnetic field is represented by white contour lines and the orientation of the transverse field is indicated by short gray lines. The 180° ambiguity has not been resolved.

Centerers, which they associate with downward drafts on the periphery of these objects. Steiner, Hauschildt, and Bruls (2001) give an explanation for the high positive contrast of small-scale magnetic flux concentrations in the photosphere when observed with the G-band filter. They found that this effect is due to a reduction of the CH abundance by dissociation in the deep photospheric layers of the magnetic flux tubes, where it is hotter than in the surrounding atmosphere.

Active region dynamics

The size spectrum of solar magnetic fields ranges from sunspots, pores, and magnetic knots to filaments and network clusters and finally to the theoretically predicted flux fibers with dimensions of just a few tens of kilometers. In active regions, magnetic fields have small-scale structures that can be
seen only in high-resolution observations, such as umbral dots, penumbral filaments, penumbral grains, running penumbral waves, moving magnetic features, filigree, moustaches, and small-scale bipoles. Typical examples of magnetic field data obtained with the digital vector magnetograph (DVMG) are presented in Figures 5 and 6 (Spiroik et al., 2001).

Sunspots are the largest magnetic concentrations on the surface of the Sun. The umbra is the dark central part of a sunspot. The penumbra is a radial, filamentary structure surrounding the umbra. The magnetic field decreases gradually from about 0.3 T at the center of the umbra to about 0.08 T at the outer part of penumbra and vanishes abruptly slightly outside the penumbra in the photosphere. The magnetic field continues as magnetic canopy (Giovanelli, 1982; Solanki, Rüedi, and Livingston, 1992) in the chromosphere outside the photospheric boundaries of the penumbra. High resolution observation show that there are fine structures inside sunspots, e.g., bright and dark filaments in the penumbra, penumbral grains, light-bridges, umbral dots, and dark nuclei observed in the umbra (Sobotka,
Bonet, and Vázquez, 1993; Sobotka, Brandt, and Simon, 1997a, 1997b, 1999; Sobotka and Sütterlin, 2001). This fine structure plays an important role in understanding the dynamics and physical nature of sunspots.

How is magnetic energy stored and released? This is a fundamental question in solar physics. Figures 7, 8, and 9 show high-resolution Hα images of flares, post-flare loops, and active sigmoidal filaments (Canfield, Hudson, and McKenzie, 1999). Solar physicists have been spending much time and effort to search for flare-related changes in the photospheric magnetic field, which would provide some clues on energy storage and release in active regions. Despite this fact, we still lack a detailed understanding on how photospheric magnetic fields evolve before, during, and after solar flares. However, new advanced instrumentation providing high-cadence and high-resolution data from ground- and space-based observatories, place is finally in a position to discover the photospheric signature of flares, in particular that of the photospheric magnetic field.

Deng et al. (2004) observed NOAA 9026 on 2000 June 6, where three major flares, an X1.1, M7.1, and X2.3 flare, originated within $2\frac{1}{2}$ hours
Figure 8. High resolution Hα data taken with the 65 cm vacuum reflector on 2001 April 15 at 22:13 UT. The image shows major post-flare loops after a flare in solar active region NOAA 9415.

near the neutral line of a large δ-spot region. Subsequently, they found an increase of MMFs, flux emergence and cancellation, and in particular the disappearance of two penumbral segments located in opposite polarity regions on the north-south side of the δ-spot. In recent studies (Wang et al., 2000a, 2002a, 2002b; Spirock, Yurchyshyn, and Wang, 2002), rapid and permanent changes of photospheric magnetic fields have been related to flare activity. The penumbral decay observed by Deng et al. (2004) is likewise interpreted as a rapid increase of the inclination angle of penumbral flux tubes, which gradually fade into the almost vertical fields of the sunspot umbrae. This sudden change of the magnetic field topology change led to an 11-degree long filament eruption and a full-halo coronal mass ejection (CME).

Some of the characteristics of the rapidly changing magnetic field topology have been related to the “magnetic breakout” model of Antiochos, Devore, and Klimchuk (1999), which can be summarized in the following statement: a magnetic breakout is the opening of initially low-lying sheared
fields, triggered by reconnection at a null point that is located high in the corona and that defines a separatix enclosing the sheared fields. The disappearance of a penumbral segment, i.e., the change from more horizontal to almost vertical fields, might just be one of the signatures indicating the opening of magnetic field lines. Another well studied event, that fits the magnetic breakout model, was the “Bastille Day” event (Aulanier et al., 2000), an M3 two-ribbon flare with subsequent CME, which occurred at 12:55 UT on 2000 July 14 in active region NOAA 8270 near disk center. In contrast to the magnetic breakout model involving multipolar magnetic field configurations, flares in bipolar regions with single neutral lines have been analyzed in terms of the classical “tether cutting” model (Sturrock, 1989).

The aforementioned studies involving the magnetic breakout model or rapid changes in photospheric magnetic fields were focussed on highly energetic events, but there are reasons to believe that smaller events in the C- and lower M-class range will show a similar signature when observed with sufficient spatial and temporal resolution, e.g., Denker and Wang (1998).
presented a high-spatial resolution time sequence of a small δ-spot, where strong proper motions of small magnetic features, i.e., the head-on collision between a small sunspot with rudimentary penumbra and a group of small pores and magnetic knots, led to a C-class flare.

10. High-resolution two-dimensional spectropolarimetry

To advance our understanding of small-scale magnetic fields, higher light gathering capacity and spatial resolution are essential, which started several initiatives for a new generation of solar telescopes with 1-meter apertures and beyond. Major efforts are undertaken in the solar physics community to upgrade existing or build new ground-based observing facilities. These efforts include the 1-meter New Swedish Solar Telescope (NSST), which is already operational (Scharmer et al., 2002); the German 1.5-meter GREGOR telescope (Volkmer et al., 2003) and the 1.6-meter New Solar Telescope (NST) at BBSO (Goode et al., 2003), which are currently under construction; and the 4-meter Advanced Technology Solar Telescope (ATST) under the stewardship of the National Solar Observatory (NSO), which approaches the end of its design and development phase (Keil et al., 2003). All these new telescopes have one common goal, i.e., to study the solar atmosphere with high-spatial resolution and suite of post-focus instruments is currently being developed for two-dimensional spectropolarimetry. In the following paragraphs, we will use the design efforts at BBSO to illustrate some of the characteristics of these instruments.

High spatial, temporal, and spectral resolution are competing factors in precision spectro-polarimetry, which leads to the question, how to slice the multi-dimensional data set (two spatial and one spectral dimension, polarization, spectral line selection corresponding to atmospheric height, and temporal evolution)? The design goals of the visible-light imaging vector magnetograph (VIM) and the NIR imaging vector magnetograph (IRIM) at BBSO are high temporal and spatial resolution observations while maintaining moderate spectral resolution $\lambda/\delta\lambda$. Both instrument operate close to the diffraction limit $a = \lambda/D$ of the 65 cm vacuum telescope and are prototypes for the post-focus instrumentation of next generation of solar telescopes. A detailed description of VIM and IRIM is presented by Denker et al. (2003). The imaging magnetographs use single Fabry-Pérot etalons as the passband defining elements and have a similar instrumental arrangement as the imaging magnetograph at Mees Solar Observatory, Haleakala, Maui (Mickey et al., 1996). A correlation tracker and a high-order AO system with 97 actuators (Didkovsky et al., 2003) provide full compensation of wave-front errors assuming fair seeing conditions with a Fried-parameter $r_0 > 6$ cm.
IRIM will be one of the first imaging spectro-polarimeters for NIR observations. Higher magnetic sensitivity (Zeeman splitting $\Delta \lambda_B \sim g \lambda^2 B$) and better seeing conditions $r_0 \sim \lambda^{6/5}$ are some of the advantages driving the development of NIR instrumentation. IRIM benefits from a larger isoplanatic angle $\theta_0 \sim \lambda^{6/5}$ and a higher Strehl ratio in the NIR, especially when operated in combination with the AO system. Diffraction limited observations over an extended field-of-view (FOV) can be achieved. Even for visible-light observations, the seeing induced cross-talk is minimized beyond the isoplanatic patch, since the tilt isoplanatic angle is substantially larger than the isoplanatic angle associated with higher order deformations.

The first Pt Si/Si NIR camera system for observations at BBSO was developed by the late Prof. Kosonocky of the New Jersey Institute of Technology (NJIT) Electrical and Computer Engineering (ECE) department. Wang et al. (1998) used this system to study the contrast of faculae at 1.6 $\mu$m. One of the design goals for IRIM is high light throughput without sacrificing spatial resolution. The maximum FOV of BBSO’s 65 cm telescope is 240$''$×240$''$. The diffraction limit at 1,564.85 nm is 0.5$''$. Therefore, a large format, 1024 $\times$ 1024 pixel detector is needed to exploit the capabilities of the 65 cm telescope. The next generation NIR detector will be a Complementary Metal Oxide Semiconductor (CMOS) focal plane array (FPA). IRIM is based on a 1024 $\times$ 1024 pixel, infrared Hg Cd Te/Cd Zn Te focal plane array developed by the Rockwell Science Center (RSC) in Thousand Oaks, California, which can provide high frame rates of up to 40 frames s$^{-1}$, high quantum efficiency ranging from 50% to 90% in the wavelength region from 900 to 2,500 nm, as well as a dynamic range better than 67 dB.

The study of magnetic fields on the sun is critical to the research of solar phenomena. Narrow pass band birefringent filters play a very important role in solar magnetographs, which measure the strength and direction of magnetic fields on the sun. Currently, most magnetographs operate in the wavelength range of visible light from 400 to 700 nm. IRIM will provide vector magnetograms with four times better spatial resolution and improved magnetic sensitivity, compared to the digital vector magnetograph (DVMG, Spirocko et al., 2001) at BBSO, due to resolved line profiles while maintaining a cadence of 1 to 4 minutes, which is necessary to follow the dynamics of small-scale magnetic fields. Usually, large sunspots possess strong magnetic fields in the order of 0.2 to 0.3 T. However, in other solar features such as plages or small bipoles in filament channels, the magnetic fields are only about 0.1 to 0.15 T. There are even weaker fields (<0.1 T) in other structures such as the intranetwork magnetic fields. The Zeeman splitting induced by these fields is too small to be measured in the visible spectrum. For example, the DVMG system at the 25 cm vacuum refractor uses the Ca I line at $\lambda = 610.3$ nm with $g = 2$. If $B = 0.1$ T then...
$\Delta \lambda = 47g\lambda^2 B = 3.5 \text{ pm}$. However, for the NIR line Fe I 1,564.85 nm with $g = 3$, the Zeeman splitting $\Delta \lambda = 35 \text{ pm}$ is about an order of magnitude larger. Therefore, weaker magnetic field strengths can be measured more precisely using near infrared lines. The use of infrared lines as probes of solar magnetic features has been discussed in detail in Solanki, Rüedi, and Livingston (1992).

IRIM has been designed for observations in the near infrared at Fe I 1,564.85 nm and 1,565.29 nm ($g = 1.53$). The magnetograph consists of an interference prefilter, a polarization analyzer, a wavelength-tunable birefringent filter, a wavelength-tunable Fabry-Pérot filter, a CMOS FPA, and a real-time data processing system. IRIM is expected to achieve a clean narrow pass band of 11.3 pm. It can be tuned across a spectral line to obtain line profiles of a two-dimensional field of view. The FWHM of the interference prefilter is about 3 nm. It is followed by an innovative Lyot-filter for near infrared observations (Wang et al., 2000c). The FWHM of the Lyot-filter is 0.25 nm. Finally, a Fabry-Pérot filter manufactured by IC Optical Systems (formerly Queensgate Instruments) restricts the pass band to 11.3 pm. The etalon has a clear aperture of 70 mm, the free spectral range is 0.52 nm, the finesse is about 60, and the transmission is expected to be better than 75%.

Since the imaging magnetograph system records a multi-dimensional data set (two spatial dimensions, wavelength, polarization, and time), it is an ideal case to explore parallel processing as an option to obtain real-time magnetic field measurements. Real-time data analysis will be the first step towards easy available high-level data products. On-site data processing of external data requests requires parallel processing of data. The overall goal is to provide well calibrated data products in a manner that one now routinely obtains with space-based experiments. The active region monitor (ARM, Gallagher et al., 2001) at BBSO is an example of the visualization of high-level data products. A common concern related to real-time data processing is a potential distrust in processed data and an overemphasis on software development rather than scientific conquest. However, cutting-edge research can only be achieved with cutting-edge instruments while educating the next generation of solar physicists to obtain an intimate knowledge of these instruments and using them to solve scientific problems.

11. Real-time image reconstruction

In recent years, post-facto image processing algorithms have been developed to achieve diffraction limited observations of the solar surface. We are using the speckle masking imaging technique, in combination with a parallel computer built by 32 1.8 GHz AMD Athlon processors, to yield
near real-time time-series with a cadence of approximately 1 min, which is sufficient to resolve the evolution of solar surface phenomena, such as granulation, pores, sunspots and including the fine-structure of sunspot umbrae and penumbrae. The predecessor of this system has been described in Denker, Yang, and Wang (2001). The first images reconstructed by the new RTIR system are shown in Figures 3 and 4.

Since a speckle image consists of a mosaic of reconstructed isoplanatic patches, there is in principle no limitation of the FOV which is only limited by the detector size and the computational effort (Denker, 1998). This is one advantage of speckle imaging over AO which corrects only over a FOV comparable to the isoplanatic patch, even though the image quality improves over larger FOVs. On the other side, speckle imaging requires a relatively high signal-to-noise ratio for the short-exposure images which limits its application to narrow band filtergrams with pass bands of about 10 pm. The practical limits of the speckle masking method have probably been reached in a study of granular dynamics by Hirzberger et al. (2001) who achieved a spectral resolution of 3.5 pm and a spatial resolution of about 0.5". Speckle masking imaging and AO are complementary with respect to spectral resolution and FOV. However, they could be combined if a solution is found for non-ergodic speckle transfer functions (STFs).

The power of parallel computing has not yet been exploited in solar physics. Supercomputers have been used for numerical calculations in astrophysics, however, they cannot be used for real-time data processing because the observational data cannot be transferred to the supercomputer centers in real-time. Usually, only a few data sets are analyzed per year, and only at the end of this process does one discover if something really interesting has been captured. The time-lag between the observation and the data analysis is far too long for any sort of rapid response, such as would be needed for space weather warnings and flare forecasting. Furthermore, the time lag renders the whole scientific enterprise less efficient than it needs to be, considering today’s computer technology. Parallel processing of solar data will literally provide a new window through which we can observe the sun in exquisite detail and study the evolution of granulation, sunspots, prominences, and flares. The underlying data processing algorithms are understood, but the complexity is such that only parallel computing enables us to visualize and interpret large data sets effectively.

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