Academy of Sciences of the Czech Republic

Astronomical Institute

Fine Structures in and around Sunspots and Pores

Dissertation submitted for the degree of Doctor Scientiarum

by

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to my father

Abstract

This dissertation is dedicated to the analysis of white-light, infrared and spectroscopic observations of sunspots, pores and other photospheric structures in active regions. These observations were acquired at four large solar telescopes located at the observatories on Canary Islands, which provide data with high spatial resolution necessary to study sub-arcsecond (fine-structure) elements in the solar photosphere.

In the introductory part, we give a review about the history and current status of the research on sunspots, pores, umbrae and umbral dots, light bridges, penumbral filaments and grains, photospheric faculae and dynamics of photospheric structures in active regions. This review is focused to the fine structures at the photospheric level.

In the second part, we summarize the principal results:
Umbral dots are very small, bright point-like features embedded in umbrae of sunspots and pores. They are observed just at the resolution limit of large solar telescopes. We have measured their brightness, size, lifetime, spatial distribution and horizontal motions and we discuss their contribution to the heating of umbrae. We found that the brightness of umbral dots is related to the brightness of adjacent umbral background. We also claim that the majority of umbral dots can be spatially resolved with a 1-m telescope.
Light bridges are bright elongated structures that separate umbral cores or penetrate deep into them. We have proposed their morphological classification and studied their internal structure, concluding that light bridges have a convective origin.
Penumbral grains are local brightenings in penumbral filaments. We have measured their horizontal motions, photometric characteristics and lifetimes. We found that most penumbral grains move inwards, toward the umbra, in the inner penumbra and outwards in the outer penumbra.
We have studied the *motions of granules* in the vicinity of pores and found that some of them, pushed by mesogranular motions, penetrate into the pores' umbra.
We have measured the brightness temperatures of *photospheric dark faculae* and discussed them in terms of the efficiency of convective energy transport and lateral radiative heating in magnetic flux tubes with different diameters.

The last part contains twelve original research papers and two review papers where we have published the results listed above. The presented results have contributed to the successive research on sunspots, pores and active regions and have been employed as inputs for theoretical models.

Contents

Preface

This dissertation was elaborated at the Astronomical Institute of the Academy of Sciences of the Czech Republic (ASCR) in Ondřejov and is focused to high spatial resolution observations of sunspots, pores and photosphere in active regions. The work started during my post-doctoral stay at the Instituto de Astrofísica de Canarias in Spain (1990–1992) and continued in a close collaboration with this institute, with Kiepenheuer-Institut für Sonnenphysik in Freiburg (Germany) and Karl-Franzens Universität in Graz (Austria).

The observations were acquired at large solar telescopes located at the observatories of the Instituto de Astrofísica de Canarias on the islands Tenerife (Observatorio del Teide) and La Palma (Observatorio del Roque de los Muchachos). These telescopes are:
The former Gregory-Coudé Telescope on Tenerife, operated till 2002 by the Göttingen University.
The former 0.5-m Swedish Vacuum Solar Telescope (SVST) on La Palma, operated till 2000 by the Royal Swedish Academy of Sciences.
The Dutch Open Telescope (DOT) on La Palma, operated by the Utrecht University.
The 1-m Swedish Solar Telescope (SST) on La Palma, operated by the Royal Swedish Academy of Sciences.

The presented results were obtained under the ASCR Key Project K1-003-601, four grant projects financed by the Grant Agency of ASCR (303111, A3003601, A3003903, A3003404) and one grant project by the Czech Science Foundation (205-97-0500). An important support was received from Spanish Ministerio de Educacion y Ciencia, Deutsche Forschungsgemeinschaft, Instituto de Astrofísica de Canarias, U.S. Air Force Office for Scientific Research and European Solar Magnetism Network (financed by the European Commission).

The dissertation is divided into three chapters. A review about the history and current status of the research topics is given in the first one. The second chapter summarizes and comments the principal results presented in the dissertation. References are appended to the end of this chapter. The last chapter contains 12 original research papers published in refereed international journals and 2 review papers published in conference proceedings. In Chapters 1 and 2, these papers are marked by numbers in brackets to distinguish them from other references. Their list can be found at the beginning of Chapter 3. Lists of citations are attached to each paper.

The presented results have contributed to the general knowledge and to the successive research on sunspots, pores and active regions. They have also been employed as inputs for theoretical models of these phenomena.

Chapter 1

Introduction

1.1 Sunspots and pores

Our Sun is an enormous laboratory for the study of the interaction between moving plasma and magnetic fields. All the phenomena connected with the solar activity like flares, prominences, coronal loops, faculae, sunspots and pores are manifestations of this interaction. Of them, sunspots were the first to be discovered and are in fact the first astrophysical objects where magnetic fields have been found. An extensive review on sunspots was recently published by Solanki (2003).

1.1.1 History

Occasional naked-eye observations of sunspots reported by Chinese observers date back to as early as 165 BC (Xu et al. 2000). In Europe, large sunspots were sometimes misinterpreted as transits of planets across the solar disk. The situation changed after the introduction of the telescope in astronomy around 1609. Around 1611, independent discoveries of sunspots were made by Fabricius (Holland), Scheiner (Germany) and Galileo (Italy). These early observers distinguished immediately the dark central part of a sunspot, called *umbra*, and the outer not so dark annular region, *penumbra*.

In 1769, A. Wilson noticed that the penumbra of a circular sunspot near the solar limb was narrower on the centre side than on the limb side and made a correct interpretation that the umbra was located deeper than the surrounding solar photosphere. The difference in heights is called *Wilson depression*. Statistical rules on sunspots' occurrence and the solar cycle were discovered in 19th century. The application of spectroscopy made it possible to begin with the astrophysics of sunspots. Hale (1908) first reported the presence of strong magnetic fields in sunspots. Two years earlier, he derived from intensities of spectral lines that the temperature in sunspots is lower than that in the photosphere. Evershed (1909) discovered a wavelength shift and asymmetry of spectral lines formed in the penumbra. This effect has been interpreted as a Doppler shift caused by a radial, nearly horizontal flow across the penumbra.

1.1.2 General characteristics

The morphology of sunspots varies from isolated, unipolar and circularly symmetric spots to large and highly asymmetric groupings with mixed polarities. Their typical diameters range from 6 to 40 Mm or more. In case of young and irregular sunspots, often only some sectors of the penumbra are developed. Pores are small sunspots without the penumbra, with typical diameters 1–6 Mm. They often appear in groups. Near large pores, some transient filamentary structures resembling the penumbra can be observed. Typical lifetimes of sunspots range from days to weeks; large spots live longer than small ones. Sometimes sunspots survive for a few months and, with the solar rotation, they return several times to the visible hemisphere. Pores live only a few days.

Sunspots and pores are often formed by merging of small magnetic elements, motions of which are driven by supergranular and subsurface flows(e.g. Wang & Zirin 1992, Keil et al. 1999). Small flux elements coalesce into small pores and spots. In further development, these "fragments" converge and merge one another, until a large sunspot is created. The fragments keep their identity during the lifetime of a sunspot (García de la Rosa 1987) and in developed umbrae they are observed as *umbral cores* (separated parts of the umbra) or dark nuclei inside an umbral core. Bright small-scale structures (umbral dots and light bridges) are seen at the interstices of fragments both in sunspots and pores.

According to contemporary measurements (e.g. Martínez Pillet 1997), magnetic field of a large sunspot has a maximum value approaching 3000 G at the centre of the umbra. The field strength decreases monotonously outwards. Its inclination to the normal increases from zero at the centre to about 40° at the umbral boundary and about 70° at the outer edge of the penumbra. In pores (e.g. Sütterlin 1998; Keil et al. 1999), the maximum magnetic field strength is of 1700 G and the inclination on the pore's boundary varies between 40° and 60° . Field strengths and inclinations observed in individual sunspots and pores show a considerable scatter and may differ from the values mentioned above. Keppens & Martínez Pillet (1996) found that the magnetic field is extended beyond the visible radii of sunspots and pores, so that the *magnetic radius* is larger than the visible one by factor of about 1.3.

Sunspots and pores are substantially darker than the surrounding photosphere. The minimum brightness in sunspot umbra ranges typically from 0.05 to 0.3 in units of the mean photospheric intensity I_{ph}. Pores are less dark than sunspots and their minimum intensities are observed in the range of 0.2–0.7 I_{ph}. The typical brightness in the penumbra is varying between 0.60 and 0.95 I_{ph} (Collados et al. 1988).

Early observations suggested that large sunspots are darker than small ones. Such observations were often insufficiently corrected for stray light, as pointed out by Zwaan (1965). Observations made since then have usually been carefully corrected for stray light and, in fact, for sunspots with umbral diameters larger than $8''$ –$10''$ no significant dependence of brightness on umbral size were found (e.g. Albregtsen & Maltby 1981). However, Sobotka (1985), using profiles of spectral lines corrected for stray light, showed that small umbrae with diameters smaller than $7''$ –$8''$ have temperatures systematically higher than large ones. Later, Kopp & Rabin (1992) found a clear relationship between the umbral brightness at $\lambda = 1.56\,\mu$m and sunspot size. These results were confirmed independently by Martínez Pillet & Vázquez (1993). The decrease of umbral brightness with increasing umbral diameter was also obtained in Paper [3] from high-resolution white-light images of 14 umbral cores and in Paper [11] from infrared images of pores.

The relation between the magnetic field and brightness (or temperature) of umbral cores was first predicted by the theory: Regions with higher magnetic field strength B should be darker and cooler than those with lower B. This problem was extensively investigated, both theoretically and observationally. The most careful and thorough studies have been made by Kopp & Rabin (1992) and Martínez Pillet & Vázquez (1993). The latter authors, analyzing profiles of Fe I and Ti I lines observed in 8 sunspots, have found that the temperature decreases linearly with increasing B^2.

Sunspots and pores are dynamical systems. Doppler plasma motions as well as horizontal motions of small-scale structures are seen in umbrae, penumbrae and in the surrounding photosphere. Observed with moderate spatial resolution, the umbra is almost static while the penumbra shows predominantly the Evershed flow. High-resolution observations reveal a more complex picture, which will be described in the next sections.

Many sunspots are surrounded by a *moat*, an annular region free of static magnetic field (Sheeley 1969), where flows away from the spot are detected in dopplergrams (Sheeley 1972). Time series of high-resolution images and magnetograms show granules, facular points and small magnetic elements moving radially away from the penumbra through the moat (Shine et al. 1987; Muller & Mena 1987; Brickhouse & Labonte 1988; Wang & Zirin 1992; Bonet et al. 2005). It is possible that the moat outflow is a surface manifestation

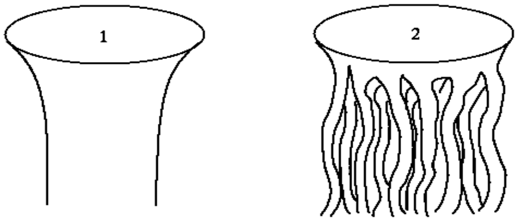

Figure 1.1: Theoretical sunspot models: 1 – Monolithic flux tube with magnetoconvection, 2 – Cluster of thin flux tubes.

of a convective "collar" that contributes to the stability of the sunspot (e.g. Meyer et al. 1974).

1.1.3 Theoretical models

According to Cowling (1934), sunspots are formed by magnetic flux tubes breaking through the solar photosphere. On the basis of this assumption Biermann (1941) suggested that the darkness of sunspots could be explained in terms of restriction of convection by the magnetic field. Since then, numerous theoretical models have been developed to describe sunspots and pores. They are briefly reviewed in Paper [14]. Observations show that sunspots and pores, in spite of appearing very dark in white light, are still relatively hot (for orientation, effective temperatures in umbrae are of about 4000–4500 K), so that the energy transfer cannot be suppressed completely and some kind of convection should be present there. The two following classes of theoretical models are the most important (Fig. 1.1) :

1. A sunspot (pore) is formed by a monolithic but inhomogeneous flux tube with magnetoconvection inside. Models of magnetoconvection describe the modification of plasma flows by magnetic field and, at the same time, the changes in the magnetic field due to plasma motions. In 3D non-linear numerical simulations of magnetoconvection in compressible fluid, structures similar to the observed ones appear: Umbral dots, light bridges and penumbral grains (e.g. Weiss et al. 1996, Rucklidge et al. 2000, Hurlburt et al. 2000). Moreover, observed horizontal motions of the fine structures are also reproduced by these models.

2. A sunspot (pore) is formed by a tight bundle of isolated thin flux tubes, separated by field-free plasma which can penetrate into layers near to the visible surface. This "cluster" or "spaghetti" model was proposed by Severny (1965) and by Parker (1979a,b). Umbral dots and light bridges can

be explained as radiative signatures of field-free columns of hot gas intruding between the magnetic flux tubes (Choudhuri 1992).

Although these two approaches start from very different presumptions, they predict quite similar observable effects and both of them can be used to explain the heating of umbrae as well as the existence of observed fine structures. To decide which model describes better the reality, it is necessary to obtain observational data from deep layers below the visible surface. Hopefully, the local (time-distance) helioseismology will shed more light on this problem in the near future.

1.2 Sunspot fine structures

1.2.1 History

Observations of sunspots and pores with high spatial resolution have a long history. In 1870 appeared the first edition of the book *Le Soleil* by P. A. Secchi. Most of the basic concepts of the sunspots' morphology can be found there. Secchi made visual observations in the period 1865–1870 with a resolution approaching to $0\farcs3$ in some cases. In his wonderful drawings he presented not only the basic morphological features like multiple umbrae, light bridges and penumbral filamentary structure, but also "knots" in bright penumbral filaments (penumbral grains) and internal structure of light bridges. He also noticed spatial variations in umbral brightness and the darkest regions – "holes"– in the umbra (dark nuclei). In three of his drawings even some umbral dots can be seen, although he did not describe them.

A large collection of sunspot photographs with spatial resolution of $0\farcs7$–$1''$ was published by Chevalier (1916). The presence of many visually observed structures was confirmed there and, moreover, a small-scale granular-like pattern in the umbra was discovered. The existence of *umbral granulation* was confirmed later by several observers (Thiessen, 1950; Rösch, 1957; Bray and Loughhead, 1964; Bumba, Hejna, & Suda, 1975). Bumba & Suda (1980) claimed that the spatial distribution of "granules" inside the umbra is identical with that in the photosphere.

A new concept in umbral fine structure was introduced by Danielson (1964). In the photographs from the balloon-borne experiment Stratoscope he detected very small, bright point-like features that he called *umbral dots*. The spatial distribution of umbral dots was quite different from the photospheric granulation pattern. Since that moment, there were two parallel concepts, umbral granulation and umbral dots, concerning probably the same effect. This ambiguity was resolved during the 1980s, when new instruments and observing techniques made it possible to get systematically images with

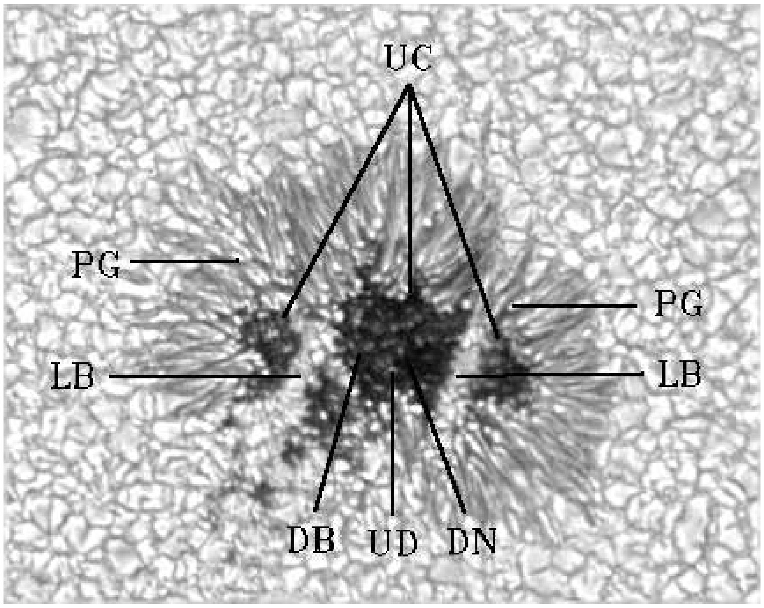

Figure 1.2: Illustration of basic fine-structure elements in sunspots: UC – umbral core, PG – penumbral grain, LB – light bridge, DB – diffuse background, UD – umbral dot, DN – dark nucleus (reprinted from Paper [13]).

a resolution better than $0\overset{''}{.}5$. It seems now that umbral granules corresponded to groups and clusters of umbral dots, detected in moderate-resolution observations ($0\overset{''}{.}5$–$1''$), and that the partially resolved umbral intensity pattern resembled apparently the photospheric granulation.

The penumbra is formed by bright and dark filaments. Analyzing a series of high-resolution photographs taken at Pic du Midi, Muller (1973a,b) pointed out that the bright filaments are often composed of aligned *penumbral grains* – elongated bright features having cometary-like shapes with “heads” pointing toward the umbra.

1.2.2 Overview of sunspot fine structures

Let us briefly summarize the nomenclature of the basic fine-structure elements, specified in Papers [3] and [13]. See also the illustration in Fig. 1.2.

In many sunspots, instead of a single umbra, we observe multiple umbrae, which seem to behave like independent units. These are termed *umbral cores* (UC), reserving the more general term umbra for the entirety of dark areas in the spot. Umbral cores are basic umbral structures which survive the whole lifetime of the spot. From the phenomenological point of view, umbral cores consist of two components. The dark one looks like a coherent background with smoothly varying intensity forming brighter and darker regions with diffuse transitions. For this reason we call it *diffuse background* (DB). The well-distinguished darkest regions (local intensity minima) are called *dark nuclei* (DN). The bright component, embedded in the diffuse background, is formed by *umbral dots* (UD) or clusters of them and by faint light bridges.

Light bridges (LB) show a large variety of sizes, brightnesses, and shapes. Some of them separate umbral cores, being a substantial part of the sunspots' configuration, others are located inside umbral cores, forming, together with umbral dots, the umbral bright component.

The penumbra of sunspots is formed by *bright filaments* separated by narrow *dark fibrils*. In a regular spot, the filaments cross the penumbra almost radially. Young and irregular spots often develop only parts of the penumbra. In bright filaments, chains of aligned *penumbral grains* (PG) are often observed. At the inner penumbral boundary, some penumbral grains penetrate into the umbra as *penumbral extensions*. Observations with extremely high spatial resolution of $0\farcs12$, acquired with the 1-m Swedish Solar Telescope on La Palma, revealed an internal structure of penumbral grains (Rouppe van der Voort et al. 2004) and dark cores in penumbral filaments (Scharmer et al. 2002).

1.2.3 Umbra and umbral dots

Sunspot umbrae often consist of several umbral cores. Each umbral core behaves as an independent unit, so that their brightness and magnetic field strength may differ strongly even in one sunspot. An important photometric parameter of umbral cores is the minimum intensity (or the intensity of the darkest point), which is well correlated with the average intensity of the diffuse background – see Paper [3]. This correlation, which is not obvious due to a significant inhomogeneity of the background intensity, allows to characterize the entire brightness of the diffuse background by a single, easily measurable value.

The darkest regions in umbral cores, dark nuclei, are the areas with the strongest magnetic field, which is nearly perpendicular to the solar surface. They are not necessarily located at the centres of umbral cores. Few umbral dots are seen inside them and some dark nuclei appear void even in the best-quality frames.

Umbral dots are tiny bright point-like structures embedded in the umbral diffuse background (Fig. 1.3). They appear in umbral cores as well as in pores. Excellent seeing and a telescope of at least medium size (resolution better than $0\farcs3$) are necessary to observe them, often at the resolution limit.

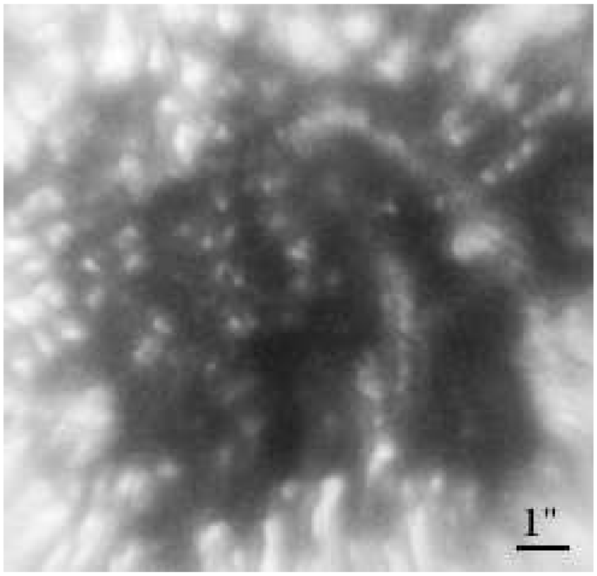

Figure 1.3: Umbra with umbral dots and dark nuclei. The image was taken on 20 September 2003 with the 1-m Swedish Solar Telescope, La Palma (Paper [12]).

Much effort has been devoted to determine temperatures, sizes and, more recently, magnetic fields and velocities in umbral dots.

For many years, the temperature measurements have been based on photometric techniques. Observations in a single wavelength band provide brightness temperature, which is, however, influenced by image degradation caused by the telescope and seeing. Two-colour photometry circumvents this problem but it is not straightforward to physically interpret the obtained colour temperature, because the radiation in the two different wavelengths comes from different geometrical heights with different temperatures. This method was first applied to umbral dots by Beckers & Schröter (1968) and Koutchmy & Adjabshirzadeh (1981). They found that the colour temperatures and brightnesses of umbral dots are similar to those of the quiet photosphere and the diameters are of 150–200 km. However, more recent observations indicate that the temperature and brightness vary in a broad range, mostly below the photospheric values. The brightness of umbral dots seems to be related to the brightness of the adjacent diffuse background, as indicated by Sobotka et al. (1991). This relation was studied in detail in Papers [1], [2], [3], [12] and confirmed by Denker (1998) and Tritschler & Schmidt (2002). On average, umbral dots are 1.3–1.8 times brighter than the background when observed directly in white-light images. Applying the two-colour photometry or a two-component thermal semi-empirical modelling to umbral dots (Papers [2], [3] and [12]), their calculated brightness is approximately three times higher than that of the local diffuse background.

For the magnetic and Doppler velocity measurements, spatially-resolved profiles of spectral lines are required (and Stokes spectra highly desirable). The first spectroscopic observations of umbral dots were probably those of Kneer (1973). Analyzing the Zeeman splitting in intensity spectra, he obtained a substantial magnetic field reduction of almost a factor two with respect to the surroundings. Other authors have reported a moderate field weakening of about 15 % (Pahlke & Wiehr 1990; Wiehr & Degenhardt 1993; Schmidt & Balthasar 1994; Tritschler & Schmidt 1997; Socas Navarro et al. 2004), or no weakening at all (Buurman 1973; Zwaan et al. 1985; Lites et al. 1991).

The velocity measurements carried out so far indicate that umbral dots are either at rest with respect to their surroundings (Zwaan et al. 1985; Schmidt & Balthasar 1994; Wiehr 1994) or undergoing small upflows of up to 300 m/s (Lites et al. 1991, Socas Navarro et al. 2004). On the other hand, Kneer (1973) and Pahlke & Wiehr (1990) reported strong upflows between 1 and 3 km/s. Rimmele (2004) measured upflows of 1 km/s using a line that forms close to the continuum level, but he obtained less than 300 m/s with another line formed 300 km higher in the atmosphere.

The discrepancies in magnetic field strength and velocities found by different authors might be caused by usual difficulties met when studying umbral dots spectroscopically: Stray light and insufficient spatial resolution. Nevertheless, the most important issue is the formation height of spectral lines. A substantially reduced magnetic field and high upflow velocities are derived from low-forming lines, but when using lines formed higher in the atmosphere, umbral dots are practically invisible concerning the magnetic field and Doppler velocity.

To interpret this fact, Degenhardt & Lites (1993a,b) proposed a magnetohydrodynamical model of an "umbral flux tube", representing an umbral dot. The shape of the umbral flux tube was similar to a bottle with a $d = 300$ km base located 200 km below the $\tau = 1$ level and a $d = 100$ km neck 300 km above $\tau = 1$. The magnetic field strength at the base was 300 G, while outside the tube, in the umbra, it was 3000 G. On the top of the model, at the neck, the magnetic field strength inside and outside the tube was equal. A stationary plasma upflow (15 m/s at the base) was present in the tube. The continuum intensity ratio produced by this model was estimated to 2.5. With spectral lines formed at the top of the model, no magnetic field fluctuation can be detected. The diameter of the upper part of the tube is so small that the observed upflow is below the error of measurement.

Some aspects of the above-mentioned theoretical model were recently confirmed by Socas Navarro et al. (2004). From the inversion of Stokes profiles of 8 umbral dots they found that umbral dots are hotter than the surrounding umbra only in layers deeper than 100 km above $\tau_{5000} = 1$. The magnetic field is weaker by 10 % than in the umbra and it is inclined 30° – 40° to the normal. The inclination decreases with height, indicating a possible magnetic canopy (a "bottle neck") above the dot. Upflow of about 200 m/s was detected.

Considering the basic theoretical models of sunspots and pores (see Sect. 1.1.3), umbral dots are manifestations of either oscillatory magnetoconvective plumes in a monolithic flux tube (see the review by Thomas & Weiss 2004 and references therein) or field-free columns of hot gas intruding between magnetic flux tubes in the cluster model (Choudhuri 1992). In both cases, the models are consistent with observations, predicting a reduction of magnetic field and an upflow in low atmospheric layers. A complementary mechanism of energy input to umbral dots was suggested by Hamedivafa (2003) and Hamedivafa & Sobotka (2004): At the end of its life, the lateral pressure balance of a volume of hot gas (umbral dot) is perturbed, the volume shrinks and, as a consequence of the increasing field gradient at its border, Joule heating can sustain the umbral dot brightness for a certain period.

1.2.4 Light bridges

Light bridges (Fig. 1.4) are bright elongated structures that separate umbral cores or are embedded in the umbra (see Papers [3], [4] and [14] for a detailed description of the morphological classification). Their internal structure depends on the inclination of local magnetic field and can be granular, filamentary, or a combination of both. Their width varies from less than 1″ to several seconds of arc and the brightness can range from the intensity of faint umbral dots up to the photospheric one. Some light bridges show long narrow dark lanes running parallel to the axis of the light bridges (Berger & Berdyugina 2003).

Many observations confirm that magnetic field in light bridges is much weaker compared to the umbra (Beckers & Schröter 1969; Abdusamatov 1970; Kneer 1973; Lites et al. 1991). In addition to the field reduction, Wiehr & Degenhardt (1993) and Rüedi et al. (1995) reported a higher inclination to the normal of the field vector. Leka (1997) claimed that the magnetic field is lower by 500–1200 G and more inclined than in the surrounding umbra but less than in the penumbra. Recently, Jurčák et al. (2006) have shown that in light bridges the field strength increases and the inclination decreases with increasing height in the atmosphere. This indicates the presence of a magnetic canopy above a deeply located field-free or weak-field region that forms the light bridge.

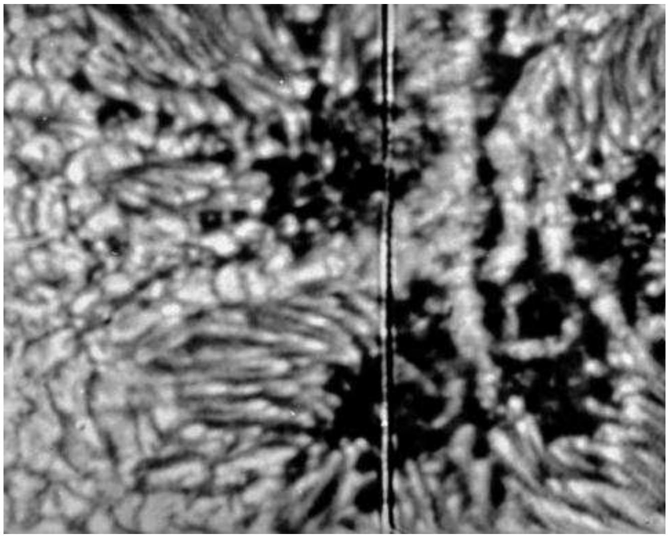

Figure 1.4: Granular light bridges in sunspot (AR 6709). The slit-jaw image was taken on 6 July 1991 with the 0.5-m Swedish Vacuum Solar Telescope, La Palma (reprinted from Paper [4]).

Line-of-sight velocities show upflows and downflows with magnitudes up to 400 m/s, indicating convective motions (Paper [4]; Leka 1997). Convective elements similar to granulation with upflows in bright "granules" and downflows in dark lanes are observed in granular light bridges (Rimmele 1997). In comparison with photospheric granulation, cell sizes and velocities are smaller and lifetimes longer, which may be a consequence of remaining weak magnetic field. A similar situation can be found in abnormal photospheric granulation (Paper [4]). Observations of evolution and horizontal motions of bright "granules" also indicate the existence of convective motions (Hirzberger et al. 2002).

The evolution of light bridges is strongly related to the development of the whole sunspot. During the sunspot formation, strips of photospheric granulation compressed between approaching umbrae ("fragments") develop into light bridges. The widths and brightnesses of these light bridges decrease, and with further evolution the bridges split in chains of umbral dots. A reverse scenario is observed during the sunspot decay. From the above mentioned facts it can be concluded that light bridges are deep-formed structures – convective regions with weak (or zero) magnetic field intruding into an otherwise stable, magnetic sunspot.

1.2.5 Penumbral filaments and grains

The most typical feature of penumbral fine structures is the elongated shape, a consequence of strongly inclined magnetic field. Bright (about 1 $I_{\rm ph}$ on average) and dark (0.6 $I_{\rm ph}$) filaments can be distinguished on the first sight. Nevertheless, due to large-scale intensity variations in the penumbra, the concepts "bright" and "dark" have only a local meaning. The width of penumbral filaments was discussed by Sánchez Almeida & Bonet (1998) who claimed that, with the resolution of $0\farcs28$, most of penumbral filaments are spatially unresolved. On the other hand, Balthasar et al. (2001) found a typical width of 250 km ($0\farcs35$). Observations with spatial resolution of $0\farcs12$ have shown that some filaments are unresolved and narrower than 80 km (Rouppe van der Voort et al. 2004). Scharmer et al. (2002) discovered narrow dark cores in bright filaments; their nature is still unknown.

Important questions are, how the strength and inclination of magnetic field differ between bright and dark filaments and where the Evershed flow is concentrated. A significant effort is dedicated to solve these problems but results of observations are often confusing (see the review by Solanki 2003 and references therein). The main difficulty is that spectral lines and continua are formed at different heights in the atmosphere and that the formation heights are not equal in bright and dark (hot and cool) penumbral structures. In the first approximation, we can accept that dark filaments host more inclined magnetic field (by 30° – 40°) compared to bright filaments. The Evershed flow tends to be concentrated in dark filaments but it is also present in the bright ones. There is no clear correlation between the bright and and dark filaments and azimuthal variations of the magnetic field strength. In any case, it seems that there are two systems of magnetic field lines differing in inclination and that the Evershed flow is related to the more horizontal one.

Many bright penumbral filaments show local brightenings often situated at the filament's end pointing to the umbra (Fig. 1.5). These elongated comet-like features are called penumbral grains (Muller 1973a,b). Their brightness range from 0.84 to 1.10 $I_{\rm ph}$, and their width is of about $0\farcs5$ (Paper [8]). Penumbral grains are dynamical objects. Muller (1973a) used a series of 34 white-light photographs, covering an interval of 3 h, to track visually penumbral grains in order to determine both velocities and lifetimes as functions of position within the penumbra. He claimed that penumbral grains moved toward the umbra with maximum speed 500 m/s at the penumbra-umbra border and zero at the penumbra-photosphere boundary. The lifetimes were about 3 h in the middle part of the penumbra, and about 45 minutes in the inner and outer parts. Tönjes & Wöhl (1982), using a similar method, confirmed the results of Muller (1973a) but found lower horizontal velocities with a maximum of 330 m/s. Lifetimes ranged from 1 to 3 h.

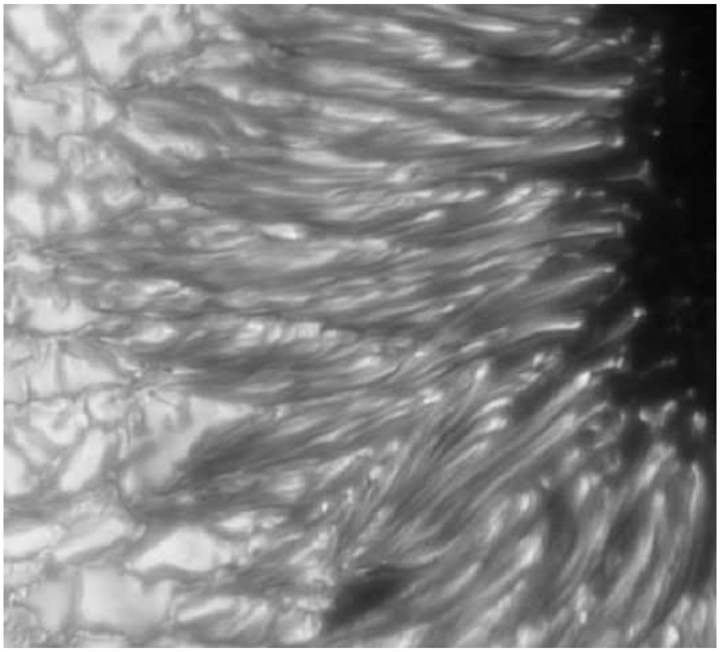

Figure 1.5: Penumbral grains observed on 18 June 2004 with the 1-m Swedish Solar Telescope, La Palma (observers M. Sobotka, K. Puschmann and C. Möstl).

The horizontal motions in penumbrae can be measured using local correlation tracking (LCT, November & Simon 1988). Because LCT does not distinguish between motions of bright and dark structures, it is not clear that LCT of a sunspot penumbra is tracking solely penumbral grains, or also other features. For example, it is known that in the outer penumbra, dark cloud-like features move rapidly (up to 3.5 km/s) towards the photospheric granulation (Shine et al. 1994). Wang & Zirin (1992) applied LCT to series of images of 5 sunspots and in four cases they reported motions of both bright grains and dark fibrils toward the umbra in the inner part of the penumbra and outward motions in the outer part. In one case the inflow occurred over the whole penumbra. Denker (1988) reported that a line of positive divergence divides the penumbra, implying opposite directions of motion in the inner and outer parts.

In Papers [8] and [9] we applied a feature-tracking technique to two series of sunspot images, one of them restored using the speckle masking algorithm, in order to accurately track the motions and to measure the lifetimes of penumbral grains. We found a dividing line in the penumbra, approximately 2/3 of the distance from the umbra to the spot's border, such that most penumbral grains outside this line moved outwards with average speed of 750 m/s and those inside moved towards the umbra (average speed 500 m/s). The lifetimes were shorter than those obtained by Muller (1973a) and Tönjes &

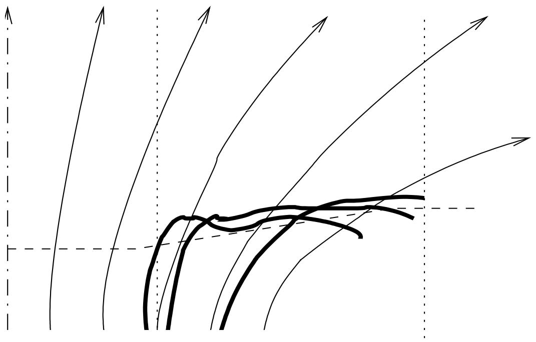

Figure 1.6: A scheme of uncombed penumbral model. Borders of umbra and penumbra are marked by dots, the visible surface by dashes. Solid lines represent two systems of magnetic field.

Wöhl (1982). The detailed results are presented in Sect. 2.3.3. The question, what happens with the outward-moving penumbral grains when they reach the penumbra-photosphere boundary, was discussed by Bonet et al. (2004). They have shown that about 1/3 of grains escape from the penumbra and penetrate into the surrounding granulation where the grains continue their outward motion, either as small bright features, or growing as expanding granules.

It is difficult to make a physical description of complex penumbral structures and their dynamics, including the Evershed effect and horizontal motions of penumbral grains. Let us mention two promising models, which may provide a basis for a future development.

The *uncombed penumbral model* was suggested by Solanki & Montavon (1993). An array of spatially unresolved, nearly horizontal flux tubes rooted in deep layers is embedded in a magnetic field with radially variable inclination angle (Fig. 1.6). This background field corresponds to the global magnetic field of the sunspot. Field strengths in both systems of magnetic field can be equal or they can differ. The horizontal flux tubes are expected to conduct the Evershed flow. Observational evidences for this model were given by Martínez Pillet (2000) and Westendorp Plaza et al. (2001). The latter authors have found that in outer penumbra the magnetic field and Evershed flow have a down-directed component.

The *moving tube model*, elaborated by Schlichenmaier et al. (1998), attempts to explain simultaneously the Evershed flow and the motion of penumbral grains. This model describes the rise to the surface of a thin magnetic flux tube from the boundary layer between the sunspot and its non-magnetic surroundings. During this motion, a hot upflow develops along the tube, which is observed at the surface as Evershed flow. The crossing point of the tube with the visible surface is observed as a penumbral grain. The rise of the flux tube causes a radial inward motion of the crossing point. This model was further developed (Schlichenmaier 2002) and a wavy shape of the flux tube was introduced to explain also the observed outward motions of penumbral grains.

1.3 Photosphere in active regions

1.3.1 Horizontal motions and structural changes in the vicinity of pores

Motions of magnetic structures, faculae, pores and sunspots, provide important information about the dynamics and evolution of active regions. They can be determined by tracking magnetic structures during periods of several hours. For example, Brants & Steenbeek (1985) found that the pores in an emerging region are located in a ring that expands predominantly in the east-west direction with a velocity of 700 m/s and with an almost negligible rotation. Strous et al. (1996) showed that pores move along the edges of an active region toward the major sunspots of their own magnetic polarity and that the major sunspots move apart. The separation velocities between objects of opposite polarities were determined for pores, facular elements and sunspots. On average, preceding structures moved faster than the following ones.

Solar pores do not develop moats like sunspots. Wang & Zirin (1992) reported converging flows around pores with speeds of 500 m/s and coherence scales of 2000–3000 km. However, Denker (1998) did not find this type of motions. We thoroughly studied this problem in Paper [10] and came to the conclusion that the motions of granules in the vicinity of pores are driven by mesogranular flows (see Sect. 2.4.1). Hurlburt & Rucklidge (2000) conducted numerical modelling of pores and sunspots as flux tubes in a compressible convecting atmosphere. In their calculations, fluid motions at the surface converge toward the flux tube.

A related problem is how the granulation is affected by the emergence of new magnetic flux or by the formation of a horizontal magnetic field inside the active region. Miller (1960) and Brants & Steenbeek (1985) detected alignments of granules and intergranular lanes. According to Wang & Zirin (1992), these alignments either connect magnetic elements of opposite polarity or correspond to unipolar fields. Such effect, related to a temporary intrusion of an opposite magnetic polarity, is described in Paper [10]. It is also well known that the properties of the granulation are affected by the magnetic field in facular regions, giving rise to abnormal granulation (cf.

Paper [4]). Sometimes, transient filamentary regions, resembling parts of a penumbra, are attached to pores (Paper [10]; Dorotovič et al. 2002). These regions are instable and, although showing some typical penumbral features, they differ from a normal penumbra.

1.3.2 Photospheric faculae

Faculae are bright regions seen in white light near the solar limb and, in some narrow wavelength bands, also elsewhere on the disk. They are composed of small ($0\overset{\prime\prime}{.}25$) facular points discovered by Mehltretter (1974). Bright and extended faculae are observed in active regions; faint faculae form a photospheric network in quiet regions. Faculae correspond to concentrations of small-scale magnetic fields (see, for example, the review by Solanki 1999). Two competing models try to explain the observed properties of faculae by combining geometrical and thermal effects. The "hot wall" model (Spruit 1976; Knölker et al. 1985) explains the white-light brightening of faculae from the disk centre to the limb as a consequence of the entrance into the observer's field of view the hot wall of the evacuated magnetic flux tube. On the other hand, the "hot cloud" model (Rogerson 1961; Chapman & Ingersoll 1972) assumes that faculae are optically thin patches above the top of the photosphere.

A critical point is to understand how the brightness is related to the magnetic flux, going from bright faculae to dark pores. This has been simulated numerically by Spruit & Zwaan (1981), who calculated the balance between the inhibition of convective energy transport (strong in large magnetic concentrations and in deep layers) and the lateral radiative heating from the non-magnetic surroundings, which is substantial in small structures and in their upper layers due to the increase of the photon mean free path with decreasing density. They found that the transition between bright and dark structures occurs at sizes around $1''$.

Observations of photospheric structures in the infrared are of particular interest, because the opacity minimum is at 1.6 μm, so that the deepest layers of the photosphere can be probed at this wavelength. Foukal et al. (1989), Foukal et al. (1990), Foukal & Moran (1994) have published a series of papers based on such observations and have reported that many faculae are dark at the disk centre. Moran et al. (1992) found that the dark infrared contrast increases with magnetic flux above a threshold value of about 2×10^{18} Mx. Observations of an active region at 1.57 μm and 610 nm with spatial resolution of $1''$ were obtained by Wang et al. (1998). They confirmed the dark contrast of 1.6 μm faculae at the disk centre and studied its relation to the magnetic flux density.

In Paper [11] we analyzed observations of dark faculae and pores near the disk centre in infrared bands 1.55 and 0.80 μm that are formed at different heights in the photosphere. The brightness temperatures calculated for the two wavelengths were discussed in terms of the efficiency of convective energy transport and lateral radiative heating in magnetic flux tubes with different diameters. This work was extended by Sánchez Cuberes et al. (2002) who studied the centre-to-limb variations of the facular contrast and size and the relation between the facular size and intensity.

Chapter 2

Principal results

In this chapter we summarize our most important results in the context of the knowledge at the time of publication and we comment briefly their contribution to the further development of concerned topics. To obtain these results, we have elaborated several methods and techniques (for example the feature tracking algorithm) that are not described here but can be found in the papers in Chapter 3.

2.1 Umbral dots

Umbral dots (hereafter UDs) are a perpetual challenge to the observers. Papers [1], [2], [3], [5], [6], [7], [10] and [12] are dedicated to this topic. The results presented in the following sections were often used for observational constraints to the models of magnetoconvection in compressible fluid (e.g. Weiss et al. 1996, 2002; Blanchflower et al. 1998; Hurlburt & Rucklidge 2000; Rucklidge et al. 2000).

2.1.1 Brightness

Around 1990, the idea of very small UDs with approximately photospheric brightness (Beckers & Schröter 1968; Koutchmy & Adjabshirzadeh 1981) was generally accepted. On the oter hand, Grossmann-Doerth et al. (1986) reported a significant spread of brightnesses and sizes. Krat et al. (1972) measured a relative contrast of UDs with respect to the neighbouring diffuse background. Although they did not bring any conclusions in this sense, from their data it could be derived that the UDs brightness can be related to the background intensity. This peak-to-background (P/B) intensity relation was studied in Paper [1] using white-light images with spatial resolution of about $0\farcs5$, acquired with the Gregory-Coudé Telescope at the Observatorio del Teide, Tenerife, Canary Islands. We found a linear dependence of

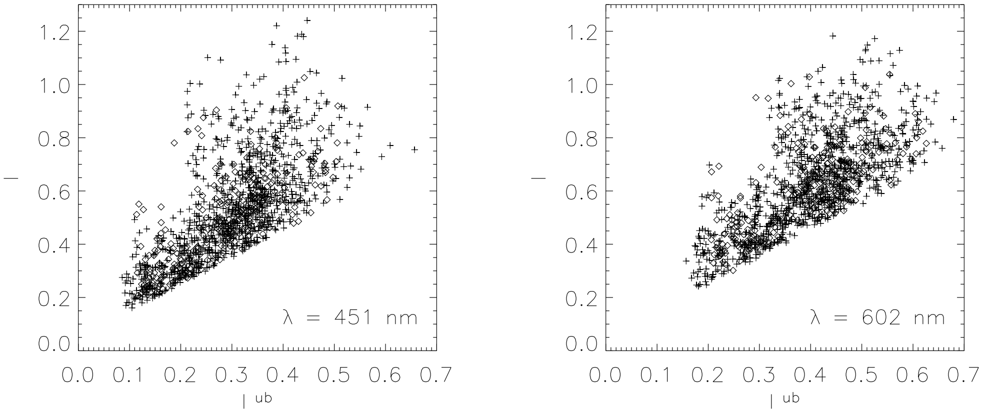

Figure 2.1: Observed peak intensities I of umbral dots versus local intensities of umbral background I^{ub} (see Paper [12]).

brightnesses of 29 UDs on the local background intensities. The real slope of this relation was determined in Paper [2]: Profiles of the Na I D lines 589.6 and 589.0 nm, observed simultaneously with the white-light images, were inverted to obtain two-component thermal models of three UDs. Using the continuum intensities calculated from the models, for the ratio of the UD and background intensities we obtained a value 2.6 ± 0.2. The results of Papers [1] and [2] were used by Degenhardt & Lites (1993b) to put observational constraints to their magnetohydrodynamical model of UDs (see Sect. 1.2.3).

The P/B intensity relation was further studied in Paper [3] on a sample of 1507 UDs, observed with the 0.5-m Swedish Vacuum Solar Telescope (SVST) at the Observatorio del Roque de los Muchachos, La Palma, Canary Islands. White-light images around 542.5 nm as well as spectra of the magnetically insensitive line Fe I 543.4 nm were recorded. In white light, the observed intensities of UDs ranged from 0.08 to 0.90 in units of the mean intensity of quiet photosphere ($I_{\rm ph}$) and they were closely related to the background intensities. The mean value of the observed P/B ratio was found to be 1.6 ± 0.3. In spite of a good spatial resolution ($0\overset{''}{.}3$), this is still an underestimate due to image degradation caused by the telescope and the turbulence in the Earth's atmosphere. To obtain the corrected value, we computed two-component semi-empirical models of 10 UDs (and 3 dark nuclei) from the observed Fe I profiles. The ratio of the calculated UD and background intensities was 3.3 ± 0.5. Taking into account the result of Paper [2], we can expect that the "true" P/B ratio is approximately equal to 3.

This fact was checked recently in Paper [12] using observations acquired with the new 1-m Swedish Solar Telescope (SST), La Palma. White-light images were taken simultaneously in two wavelength bands around 451 nm (blue) and 602 nm (red) with spatial resolution of $0\farcs15$. Scatter plots of the UD intensity versus the background intensity for both wavelengths are shown in Fig. 2.1. The points are concentrated into sector-shaped clouds, where the lower limits are determined by the UD-selection criteria. In spite of a strong scatter, a clear trend can be observed. Average values of the observed P/B ratios are 1.8 ± 0.5 (blue) and 1.6 ± 0.5 (red). The method of two-colour photometry was applied to obtain average "true" intensities. About 50 % of UDs have "true" intensities higher than the quiet photosphere and the "true" P/B ratio is 4 ± 2 (blue) and 3 ± 2 (red). This is in good agreement with the results previously obtained (Beckers & Schröter 1968; Koutchmy & Adjabshirzadeh 1981; Paper [3]). However, we suspect that this method, which is based on some unrealistic assumptions, may produce biased results.

Now it is accepted by many authors that the brightness of UDs depends on the brightness of the adjacent umbral diffuse background. This fact can be explained by both the monolithic flux tube model and the cluster model. Higher brightness of the diffuse background means lower magnetic field strength. In a weaker field, the oscillatory magnetoconvection is stronger and hot plumes that form UDs bring more energy to the surface. In case of the cluster model, the weaker field allows the field-free columns of hot gas to penetrate higher, closer to the visible surface, what results in the enhanced brightness of UDs.

Several authors (e.g. Grossmann-Doerth et al. 1986; Ewell 1992) distinguished "peripheral" UDs located in the outer parts of the umbra and "central" UDs observed in the inner parts and inside dark nuclei. Peripheral UDs are usually brighter than central ones. In Paper [7] we produced a histogram of time-averaged observed intensities of 662 UDs detected by a feature-tracking algorithm in a 4.5 h long series of images acquired with the 0.5-m SVST. The histogram clearly shows two peaks at 0.34 and 0.48 I_{ph}. A similar shape of the intensity histogram was also found by Tritschler & Schmidt (2002). This may indicate a double population of UDs in sunspot umbrae. The bright population is mostly located at or near the umbral-penumbral boundary, while the faint one occurs everywhere in the umbra. This probably led earlier observers to the division into peripheral and central UDs. On the other hand, the enhanced brightness of UDs in the vicinity of the umbral border, where the intensity of the umbral diffuse background rises towards its maximum, is simply due to the P/B intensity relation. A question remains open if the two populations are a trivial consequence of the rising background brightness at the edge of the umbra or they indicate two physically different kinds of UDs.

Temporal variations of UDs brightness were measured in Paper [7]. The power-spectrum analysis revealed several periods, among them 32 and 16

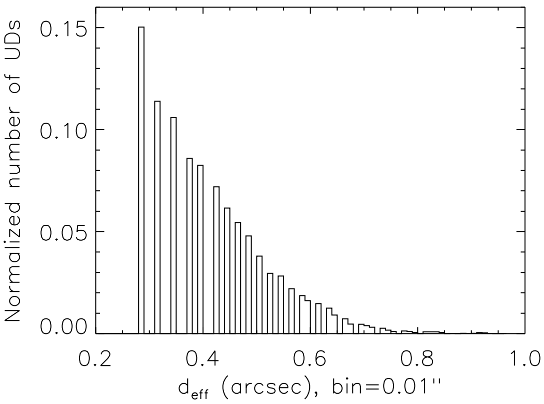

Figure 2.2: Histogram of observed diameters of UDs obtained with a 0.5-m telescope (reprinted from Paper [6]).

minutes that are similar to average lifetimes of UDs reported by various authors (see Sect. 2.1.3). The temporal variations of brightness and size were utilized by Hamedivafa & Sobotka (2004) to check for the Joule heating mechanism in UDs (see Sect. 1.2.3).

2.1.2 Size

Observed sizes (diameters) of UDs are always influenced by the finite resolution of the telescope and by the seeing. Thus the "true" sizes of UDs are supposed to be smaller than the observed ones. Their determination is closely related to the estimate of "true" brightnesses, because knowing the "true" and observed brightnesses and the observed size we can calculate the "true" size from the flux conservation law. Taking the "true" brightness equal to the photospheric one, Koutchmy & Adjabshirzadeh (1981) concluded that the diameters of UDs are very small: $0\farcs14$–$0\farcs28$ (100–200 km). Grossmann-Doerth et al. (1986) and Lites et al. (1991) tried to measure the sizes of UDs in white-light images restored for the estimated instrumental point-spread functions. They obtained $0\farcs4$–$0\farcs9$ (290–650 km) and $0\farcs17$–$0\farcs39$ (120–280 km), respectively. In the former case, Grossmann-Doerth et al. probably observed clusters of UDs rather than individual ones.

In Paper [3], using the approximate relation between the UD and background intensities, we derived the diameters to be in the range $0\farcs25$–$0\farcs41$ (180–300 km). It is worth to note that the size and brightness of UDs are uncorrelated.

In 1995 we have developed a feature tracking code (see Paper [6]) to detect small-scale features and to record their evolution in time. This procedure

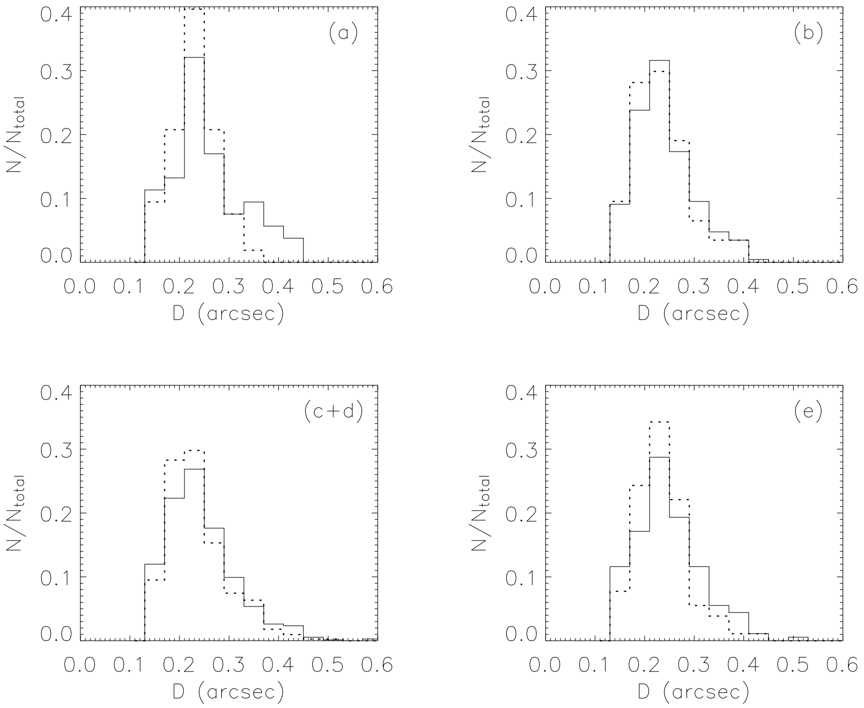

Figure 2.3: Histograms of observed diameters of UDs obtained with a 1-m telescope. *a, b* – UDs in pores, *c, d, e* – UDs in sunspot umbrae. Solid line – λ 451 nm, dotted line – λ 602 nm. The bin size is $0\farcs04$, $N_{\text{total}} = 1191$ (reprinted from Paper [12]).

returns intensities, sizes, lifetimes and positions of UDs that are not biased by observers' subjective selection. Observed diameters of 11758 UDs, identified in a 4.5 h long series of images acquired with the 0.5-m SVST, were analyzed in Paper [6]. The statistical distribution (histogram in Fig. 2.2) did not show any "typical" value. In fact, the number of UDs strongly increased with decreasing size down to the resolution limit. This result was later confirmed by Tritschler & Schmidt (2002) who, using the phase-diversity technique, corrected their observations both for the instrumental and atmospheric point spread functions, so that the resolution limit was determined only by the cut-off frequency of a 0.7-m telescope. The histogram of corrected sizes showed the same shape like that of the observed ones and the average corrected diameter was only by $0\farcs02$ smaller than the mean observed diameter. These facts implied that most of umbral dots remained unresolved by telescopes with diameters of 0.5–0.7 m.

With the new generation of the large solar telescopes of at least 1-m diameter and equipped with adaptive optics correcting the atmospheric seeing and instrumental aberrations in real time, the resolution power has been increased substantially up to nearly $0\farcs1$. In Paper [12] we used the new 1-m SST to measure sizes of UDs in two sunspots and two pores with spatial resolution better than $0\farcs15$. Histograms of observed diameters of UDs (Fig. 2.3), instead of a monotonous increase toward the smallest sizes, show a clear maximum at $0\farcs23$ (about 170 km) that can be considered a "typical" observed size. This means that the majority of UDs are spatially resolved by a 1-m telescope. A very similar histogram of sizes, peaking at 160 km, was found by Wiehr et al. (2004) for intergranular G-band bright points observed with the 1-m SST. The average "true" diameter computed for 585 UDs using the method of two-colour photometry was $0\farcs14 \pm 0\farcs06$ (100 ± 40 km). This diameter is comparable with the mean free photon path calculated at optical depth $\tau_{5000} = 2/3$, which is 90 km in the quiet photosphere and 70 km in sunspot umbrae and pores.

2.1.3 Lifetime

Lifetimes of UDs can be determined from time series of images. The first estimates were about 25 minutes (Beckers & Schröter 1968; Adjabshirzadeh & Koutchmy 1980). More recent observations made by Kitai (1986) and Kusoffsky & Lundstedt (1986) indicated longer typical lifetimes of 40 and 60 minutes, respectively. Ewell (1992) reported a mean lifetime of only 15 minutes. Several UDs were observed to exist for more than 2 h (Kusoffsky & Lundstedt 1986; Ewell 1992). It should be noted that the time resolution of all above mentioned observations was not better than 5 minutes.

In Paper [6], we obtained lifetimes of 662 UDs with a time resolution of 45 s, applying our feature-tracking code to a 4.5 h series acquired with the 0.5-m SVST. This series was the longest one available at that time with high spatial and temporal resolution. We found that 66 % of UDs had lifetimes shorter than 10 minutes, 27 % between 10 and 40 minutes, 6 % between 40 and 120 minutes and 1 % of UDs existed longer than 2 h. We did not find any "typical" value; rather, the shorter the lifetime, the more numerous UDs. This result differs from the former estimates, which were based on observations of small samples of UDs and probably influenced by visual selection effects and intensity variations of long-lived UDs.

2.1.4 Spatial distribution

The spatial distribution of UDs is an important observational input to theoretical models. UDs can be found everywhere in the umbra (Adjabshirzadeh & Koutchmy 1980). Their distribution, however, is not uniform. They form clusters and alignments at some "preferred" locations in the umbra and they

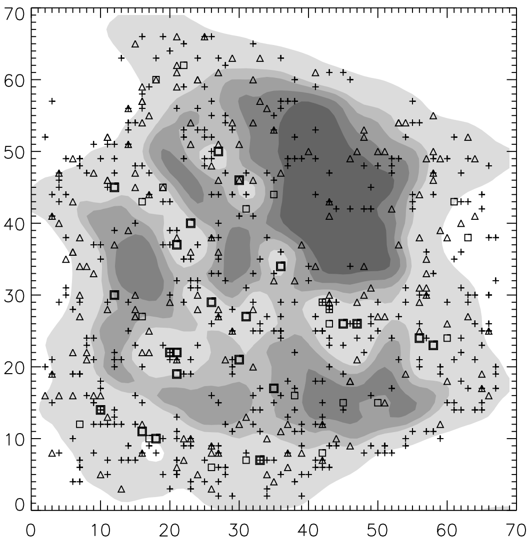

Figure 2.4: Spatial distribution of UDs with different lifetimes t: Symbol "+" represents UDs with $t \leq 10$ minutes, triangles correspond to $10 < t \leq 40$ minutes, squares to $40 < t \leq 80$ minutes, and bold squares to $t > 80$ minutes. The underlying image of the umbral core has intensity contours 0.24, 0.26, 0.28, 0.30, and 0.45 $I_{\rm ph}$. The coordinates are in pixels ($0\farcs125$/px). Reprinted from Paper [6].

are almost missing in dark nuclei. From measurements in 18 different umbral cores we found that the average nearest neighbour distance of UDs ($0\farcs5$–$0\farcs75$) decreases and the observed filling factor (the relative area occupied by UDs, 6 %–15 %) increases with increasing brightness of the diffuse background (Paper [3]).

Recently, we have refined these results using the data with very high spatial resolution ($0\farcs15$) acquired at the 1-m SST (Paper [12]). The mean nearest neighbour distance measured in 5 umbral cores was in the range $0\farcs38$–$0\farcs48$ and the filling factor based on observed areas of UDs was 9 % on average. However, we must keep in mind that the "true" areas may be substantially smaller than the observed ones, so that the "true" filling factor is only 3 %–5 % in dark and 5 %–10 % in bright umbral cores (Paper [3]).

Large ($d > 0\farcs4$) and long-lived ($t > 40$ minutes, see Fig. 2.4) UDs tend to appear in relatively bright regions of the diffuse background (Paper [6]), where the magnetic field strength is locally weaker. The brightest UDs are usually located at the periphery of the umbra (Paper [7]), where the diffuse-background intensities are high.

2.1.5 Contribution to umbral heating

It was mentioned in the preceding sections that UDs are more numerous and have higher average intensity in bright umbral cores than in dark ones. An often discussed question was if UDs are a possible source of individual differences in the mean brightness of umbrae (Adjabshirzadeh & Koutchmy 1983; Sobotka 1988; Pahlke & Wiehr 1990), in other words, if umbrae are heated by UDs.

We have studied this problem in Paper [3] and derived from our data the contribution of UDs to the mean umbral brightness in the wavelength band around 540 nm. Taking "true" filling factors 4 % in dark umbral cores and 7 % in the bright ones and using the P/B ratio equal to 3, we found that in dark umbral cores (with background brightness of 0.14 I_{ph}) UDs generate about 10% and in the bright ones (0.30 I_{ph}) about 20 % of the total energy flux. These values are too low to explain the broad range of umbral brightnesses, so that the total brightness in umbra must depend mainly on the brightness of the diffuse background. However, if the background would be heated by lateral radiation from UDs below the visible surface, umbrae strongly populated by dots could have brighter diffuse background than the less populated ones (Sobotka 2003). This possibility should be considered mainly in case of the cluster model, where UDs are expected to be tips of deeply rooted columns of hot gas.

2.1.6 Horizontal motions

Time series of high-resolution white-light images make it possible to measure horizontal motions of UDs. Ewell (1992), Wang & Zirin (1992) and Molowny-Horas (1994) reported that some UDs, perhaps associated with penumbral grains, move inwards, toward the centre of the umbra. Ewell (1992) suggested distinguishing between central and peripheral UDs on the basis of their horizontal motions – central UDs were stationary while peripheral UDs drifted inwards.

In Paper [5] we analyzed a 51 minutes long series of images, acquired at the 0.5-m SVST. The horizontal motions of umbral fine structures were determined by applying the method of local correlation tracking (LCT), described by November & Simon (1988). We observed penumbral grains moving towards the umbra. Some of them crossed the penumbra-umbra boundary, becoming peripheral UDs, and moved farther into the umbra until they met dark nuclei. Then, UDs slowed down their motion and disappeared. In some cases, the "collision" of UD with a dark nucleus was accompanied by a brightening of another UD, already existing on the opposite side of the dark nucleus. We suggested that dark nuclei, with the strongest magnetic field,

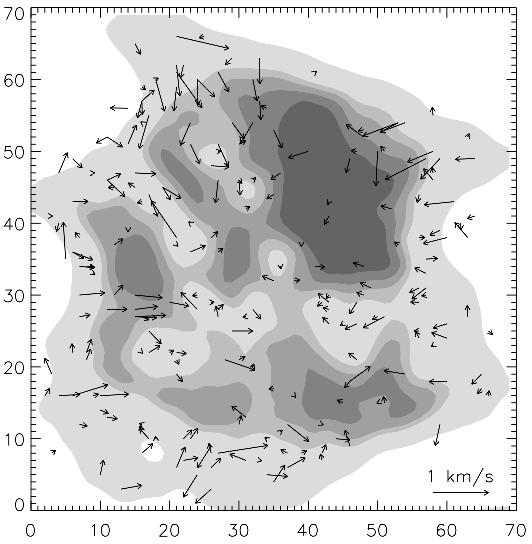

Figure 2.5: Vectors of time-averaged horizontal motion velocities for 224 UDs with lifetimes > 10 minutes. The underlying image and scale are as in Fig. 2.4 (reprinted from Paper [7]).

are dominant structures in the umbra. UDs and faint light bridges that separate the dark nuclei, probably represent different kinds of convection altered by the magnetic field.

Horizontal motions of UDs were further studied in Paper [7]. We applied our feature-tracking code to the 4.5-h series acquired with the 0.5-m SVST. The number of UDs decreases with increasing magnitude of the horizontal motion velocity and the velocity magnitude decreases with increasing lifetime of UDs. Speeds of UDs are grouped at 100 and 400 m/s. The observed spatial distribution of UDs with different horizontal velocities is shown in Fig. 2.5. Although UDs are on the average faster at the periphery of the umbra than in the central region, our results do not support Ewell's (1992) idea of moving peripheral and stationary central UDs, because both "fast" and "slow" UDs are present in all parts of the umbra.

In Paper [7], we confirmed the observation reported in Paper [5] that a "collision" of UD with a dark nucleus may be followed by a brightening of another UD located on the opposite side of the dark nucleus. If the collision and subsequent brightening are physically related, e.g. by a wave propagating across the dark nucleus, the propagation speed would be about 2–7 km/s. In general, horizontal motions of UDs are apparent, i.e., they may not represent a real mass motion. We probaly observe a wavelike translation of the convective pattern, which is halted by the stronger, more vertical

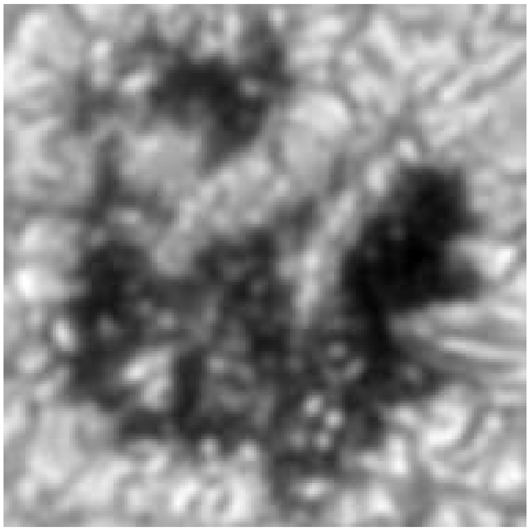

Figure 2.6: Large pore (AR 7886) observed at the 0.5-m SVST and analyzed in Paper [10]. Light bridges and UDs are clearly visible. Area of the field is $12'' \times 12''$.

magnetic field in the dark nuclei (Thomas & Weiss 2004) or, in case of the cluster model, a motion of intersections with the visible surface of the columns with hot field-free plasma.

2.1.7 Umbral dots in pores

Solar pores show the same variety of fine-scale features like sunspot umbrae – UDs, light bridges and dark nuclei (Fig. 2.6). The first detailed photometry of UDs in pores was done by Bonet et al. (1995). The observed sizes of UDs in a small pore were of about $0\overset{''}{.}7$, at the upper limit of the UD size range in sunspots.

In Paper [10], we identified and tracked the evolution of 171 UDs that appeared in a large pore (diameter $8\overset{''}{.}9$) during a 67 minute time series acquired with the 0.5-m SVST. The average observed brightness of UDs was 0.74 $I_{\rm ph}$, higher than in a sunspot umbra. The histogram of brightnesses had a single peak, in contrast to that in sunspots, which displayed two maxima (see Sect. 2.1.1). Bright UDs in sunspot umbra corresponding to the second maximum were concentrated near the umbra-penumbra border. In the pore, there was no difference between the spatial distributions of bright and faint UDs.

The histogram of sizes, derived in Paper [10], had a shape analogous to that shown in Fig. 2.2 – the number of UDs increased with decreasing size till the resolution limit $0\overset{''}{.}25$. On the other hand, UDs in two pores observed with spatial resolution of $0\overset{\prime\prime}{.}15$ (Paper [12]) had the typical observed size of $0\overset{\prime\prime}{.}23$, equal to that in sunspot umbrae (see Fig. 2.3).

The average lifetime of UDs in the pore was 19 minutes (Paper [10]), longer than that in the sunspot umbra (14 minutes, Paper [6]). The number of UDs decreased with increasing lifetime. Some UDs were present during the whole 67-minute period of observation. The velocities of horizontal motions had a median value 260 m/s (Paper [10]). The number of UDs increased with decreasing speed. The motions of UDs that were faster than 200 m/s were directed mostly inwards. The spatial distribution of UDs with different horizontal velocities was similar to that in the sunspot umbra.

In summary, UDs observed in pores are similar to those in sunspot umbrae, but they live longer, are brighter and have a higher filling factor. It seems that the UD forming process is stronger and more stable in weaker magnetic field of pores than in strong field of developed umbrae.

In Paper [6] (Sect. 2.1.6), we mentioned that some penumbral grains penetrate into the sunspot umbra and are observed as inward-moving UDs. A similar phenomenon was observed in pores and described in Paper [10]: Granular motions in the vicinity of pores are driven by mesogranular flows. Motions toward the pore dominate in the $2''$ zone around the pore boundary. Pushed by these motions, small granules and granular fragments located close to the pore border sometimes penetrate into the pore, where they move inwards as bright short-lived features very similar to umbral dots. The capture of bright features by the pore is probably a micro-scale manifestation of the "turbulent erosion" (Petrovay & Moreno Insertis 1997), which results in the decay of the pore.

2.2 Light bridges

Apart from umbral dots, other bright structures are also present in umbrae of sunspots and pores – the light bridges (LBs). Several attempts were made to establish a morphological classification of LBs (for example Bray & Loughhead 1964; Muller 1979; Bumba & Suda 1983). In Papers [3] and [4] we proposed and in [13] and [14] further specified a simple two-dimensional classification based on two parameters: (i) The morphology related to the sunspot configuration, namely, if LB separates umbral cores (strong LB) or not (faint LB). (ii) The internal structure – granular or filamentary. Thus, four basic types of LBs are distinguished: faint granular (FG), faint filamentary (FF), strong granular (SG) and strong filamentary (SF). A combination of granular and filamentary structures has been observed too. The first parameter gives an information about the role of LBs in the general configuration of the umbra, while the second characterizes the inclination of magnetic field in LBs (less inclined in granular LBs, more inclined in filamentary LBs). Our classification has been accepted by several authors (e.g. Rimmele 1997; Berger & Berdyugina 2003).

The structure of FG bridges was studied in Paper [3]. These faint LBs are composed of small bright granules (grains) with typical size of 0″.47. The mean nearest-neighbour distance of the granules is 0″.53 and their fractional area in LBs is of about 0.5, close to the fractional area granulum-intergranulum in the quiet photosphere. Two FG bridges were also observed in a large pore (Paper [10]). This observation was used later by Hirzberger et al. (2002) to study in detail the evolution and dynamics of granules in the bridges.

A photometric and spectroscopic study of two SG bridges was published in Paper [4]. The data were acquired at SVST in July 1991 with spatial resolution of 0″.3. The bright structures present in the SG bridges are generally smaller than the granules in the quiet photosphere, with typical sizes of 1″.2 (in quiet granulation, 1″.5). Spatial 2D power spectra have shown an excess of power (compared to quiet granulation) at scales of 0″.5. This power enhancement reflects the presence of small bright grains, clearly visible in LBs, with a mean nearest-neighbour distance of 0″.5 (this value is similar to that in FG bridges). Two of these small bright grains, together with a dark lane between them, were resolved in spectra of the line Fe I 543.45 nm. The bisector shapes and line shifts, showing upflows of 250 m/s in the bright grains with respect to the dark lane, indicate a convective origin of these structures. The presence of convective elements in granular LBs was confirmed later by Leka (1997) and Rimmele (1997). Taking into account the thermal and magnetic structure of light bridges described by Jurčák et al. (2006; see Sect. 1.2.4), we can conclude that LBs are deeply rooted regions with convective or magnetoconvective origin.

2.3 Penumbral grains

Penumbral grains (PGs) are local brightenings in bright penumbral filaments. They have cometary-like shapes with "heads" pointing usually towards the umbra. In the first observations, Muller (1973a,b) and Tönjes & Wöhl (1982) described inward horizontal motion of PGs toward the umbra and lifetimes of 1–3 h with the maximum in the middle part of the penumbra. Wang & Zirin (1992), using LCT, detected the inward motion but also outward motions in bright and dark filaments toward the sunspot border. We applied our feature-tracking code to the 4.5 h series of white-light sunspot images acquired with the 0.5-m SVST and determined trajectories and velocities of horizontal motions, lifetimes and photometric characteristics of 469 PGs

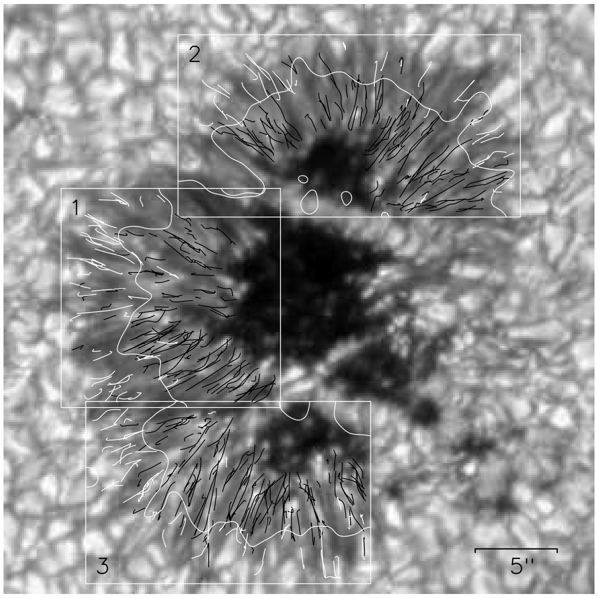

Figure 2.7: Trajectories of INW (black) and OUT (white) PGs. The white contour lines divide regions of inward and outward motions of both bright and dark features as derived by LCT. The underlying image is one of the best frames of the series analyzed in Paper [8].

(Paper [8]). These measurements were extended using a 70 minute speckle-reconstructed series of G-band (430.5 ± 0.5 nm) images of another sunspot, observed at the Dutch Open Telescope (DOT), La Palma. The speckle masking algorithm was used to correct the series for the instrumental profile of the telescope and for the influence of atmospheric seeing. A sample of 1058 PGs was studied in this case (Paper [9]). Our results were used by Schlichenmaier (2002) to improve the moving tube model (see Sect. 1.2.5).

2.3.1 Horizontal motions

The trajectories of PGs were determined from the positions tracked in time and smoothed by cubic splines. Of the 469 PGs, analyzed in Paper [8], 341 (73 %) moved inward toward the umbra. We label them INW. 128 PGs (27 %) moved outward toward the photopshere. We call them OUT. The trajectories are displayed in Fig. 2.7. Of the 1058 PGs, analyzed in Paper [9], 575 (54 %) moved inward and 483 (46 %) outward. There appears to be a dividing line in the penumbra, approximately 2/3 of the distance from the umbra to the photosphere. Outside the dividing line most PGs are of type OUT; inside most are INW. The average and maximum lengths of trajectories are $1\farcs3$ and $6''$, respectively, so none of PGs crossed the penumbra completely.

The time-averaged horizontal velocities are typically 400 m/s for INW PGs and 500 m/s for OUT PGs. Their medians differ slightly in the two observed sunspots: 430 and 520 m/s for INW PGs and 530 and 750 m/s for OUT PGs. We see that, on average, speeds of OUT PGs are higher than those of INW PGs. The velocities depend on the radial position in the penumbra. For INW PGs speeds increase from 400–500 m/s at the penumbra-umbra boundary to a maximum of 700 m/s close to the dividing line and then drop to 500–600 m/s in the outer penumbra. Speeds of the OUT PGs increase from a minimum value of 200 m/s at the penumbra-umbra border to a maximum of 900 m/s near the outer penumbral boundary. About 60 % of INW PGs decelerate their motion at least in the initial phase of their life (Paper [9]), which is partially consistent with the prediction given in the model by Schlichenmaier et al. (1998).

It is unclear to what extent the motions of PGs are associated with mass motions. Possibly, they represent only a spatial variation of brightness. In the model of moving flux tube (Schlichenmaier et al. 1998; Schlichenmaier 2002), PGs are intersections of hot parts of rising wavy flux tubes with the visible surface and their motion is not related to the gas flow inside the tubes. In the magnetoconvective approach (e.g. Thomas & Weiss 2004), the apparent proper motion of PGs is interpreted as a travelling wave, whose direction of propagation depends on the inclination of the field and is inward in the inner penumbra but outward in the outer penumbra where the field is more inclined.

2.3.2 Photometric characteristics

The time-averaged brightnesses are in the range 0.84–1.10 $I_{\rm ph}$ for both INW and OUT PGs, but OUT PGs are brighter on average (0.96 $I_{\rm ph}$) than the INW ones (0.94 $I_{\rm ph}$). The brightnesses do not depend on relative distance from the umbra and they are uncorrelated with the speeds or lifetimes of PGs. We used the best frame of the series to do complementary visual measurements of lengths and widths of 56 PGs. The lengths lie in a broad range from $0''.6$ to $3''.7$; the average value is $1''.7$. The mean and standard deviation of widths measured across the "heads" of PGs are $0''.5 \pm 0''.1$.

Balthasar et al. (1996) reported that the mean white-light image of a penumbra averaged over nearly 2 h still showed radial structures. We have confirmed this result in Paper [8]. Averaging frames over our 4.5 h series we find a filamentary structure in the penumbra with rms contrast of 7 %. For comparison, the penumbral rms contrast in our best frames is about 12 %. This remarkable persistence of high contrast over many hours must be due to the stability of the magnetic field configuration in the penumbra.

2.3.3 Lifetime

The number of PGs increases with decreasing lifetime. For INW PGs observed during the 4.5 h time series the maximum lifetime is almost 4 h but only 17 % live longer than 1 h; the median and mean lifetimes are 29 and 39 minutes, respectively. The OUT PGs live shorter than the INW ones: the maximum, median and mean lifetimes are 59, 22 and 25 minutes, respectively (Paper [8]). The 70 minute time series analyzed in Paper [9] was shorter than lifetimes of many long-lived PGs, so that we were limited only to a statistical estimate of the mean lifetime based on an average birth rate of PGs (see Paper [10] for details of the method). We obtained 50 and 30 minutes for INW and OUT PGs, respectively.

The lifetimes of INW PGs depend on the position in the penumbra: There is a maximum of approximately 1 h at about 1/4 of the width of the penumbra and then the lifetime decreases gradually to about 30 minutes at the outer penumbral border. The lifetimes of OUT PGs show only little variations with the position.

In summary, while we agree with Muller (1973a) that the average lifetime of INW PGs in the inner part of the penumbra is larger than for those near the outer penumbral boundary, we do not see the pronounced dependence of lifetime on penumbral position reported by Muller (1973a) and Tönjes & Wöhl (1982). Moreover, the lifetimes we measure are considerably shorter than those of the earlier measurements. This discrepancy, caused by different temporal resolution (30–45 s compared to 6 minutes) and by different ways we identified PGs (automated versus visual), is discussed in Paper [8]. We are convinced that our statistics are significantly better.

2.4 Photosphere in active regions

2.4.1 Horizontal motions and changes of granular structure in the vicinity of pores

In Paper [10] we employed the LCT technique to study the horizontal motions of granules around five small and one large (diameter $8\overset{''}{.}9$) pore. In all flow maps we see the typical divergent "rosetta" velocity patterns characteristic of mesogranulation (Fig. 2.8). The largest velocities in the flow field are of 1 km/s and the spatial average is 400 m/s. The emergence of pores reorganizes the mesogranular flow pattern, making the mesogranules encircle the pore boundary. Motions of granules in the vicinity of pores are driven by mesogranular flows. Motions toward the pore dominate in a zone out to a distance of $2''$ from the pore's border. The centres of mesogranules are

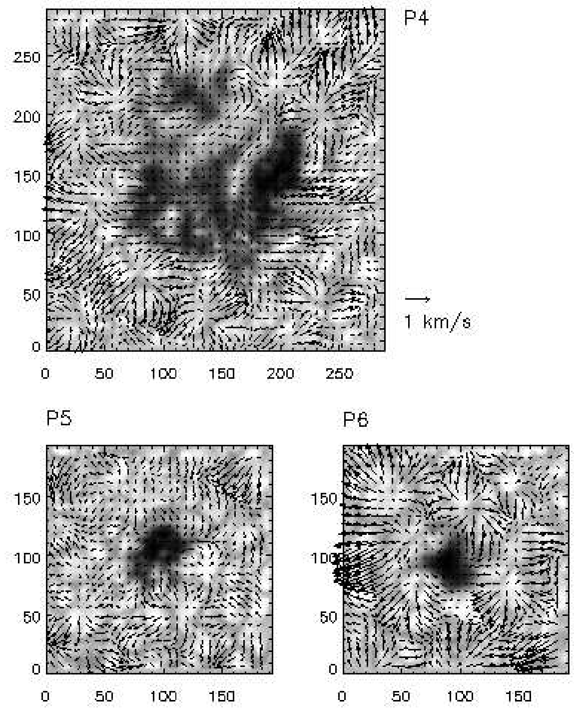

Figure 2.8: Maps of horizontal motions around pores. The coordinate unit is 1 pixel, i.e., 0″.062 (reprinted from Paper [10]).

mostly located at this distance. At larger distances, the granules move away from the pore. Roudier et al. (2002), applying LCT with higher spatial and temporal resolution, confirmed this finding. Numerical simulations of pores as flux tubes in a compressible convecting atmosphere (Hurlburt & Rucklidge 2000) show that surface fluid motions close to a pore are directed toward the pore. These flows are driven by the cooling of gas at the boundary of the cold flux tube, leading to downflows around the tube and hence converging flows at the visible surface. Our observations, however, provide an alternative explanation based on flows in mesogranules organized in a ring around the pore's border.

In Paper [10] we also described two phenomena of temporary reconfiguration of the granular intensity pattern, accompanied by strong horizontal motions of 2–3 km/s. The first consisted in the formation of a penumbra-like structure at the border of the large pore, the second in the transformation of the granular field between the large pore and another neighbour pore to a system of expanding elongated granules separated by dark filaments. Both phenomena took place near each other, parallel in time, and their duration was about 35 minutes. They can be explained as a consequence of emerging bipolar magnetic "loops" caused by a temporary protrusion of opposite magnetic polarity. A similar phenomenon was studied by Dorotovič et al. (2002) using a 11 h long series of white-light images of a large pore with an attached filamentary region. This region was changing its structure back and forth between penumbra-like filaments and elongated granules. It never developed in a sector of a normal penumbra.

In Paper [11] we described, for the first time, horizontal motions of dark faculae (together with pores) in two active regions near the disk centre. On large spatial scales, comparable to the size of active regions, we observe motions related to the separation of polarities (cf. Strous et al. 1996). Our measurements, integrated over time period more than 1 h, give the average separation speed in the range of 300–500 m/s. On small scales, below $10''$, various types of motions can be observed: a velocity system connected with the emergence of a new magnetic flux, twisting and contraction in a dark facula where a small pore was growing (here we probably observed a transformation of faculae into a pore), shear motions in a region between two neighbouring pores and a twist in a dark facula located at the border of the active region. In the last type of motion, tangential velocity components prevail. Such rotational motions that twist the footpoints of magnetic flux tubes could contribute to the heating of solar chromosphere and corona (cf. Muller et al. 1994).

2.4.2 Infrared photometry of faculae and pores

In Paper [11] we analyzed series of infrared images of two active regions near the disk centre to study how the temperature structure changes when passing from quiet granulation to faculae and pores. The data were acquired at the 0.5-m SVST simultaneously in the bands around 1.55 and 0.80 μm, corresponding to the maximum and minimum opacities, respectively. The radiation in the 1.55 μm band comes from the deepest photospheric layers and the radiation at 0.80 μm from layers several tens of kilometers higher. The spatial resolution was better than $0.''9$. Dark faculae (discovered by Foukal et al. 1989) were detected in images obtained as weighted intensity differences between both wavelength bands. The disk-centre faculae at 1.55 μm are, on average, darker by 2.5 % than the quiet photosphere.

We have calculated brightness temperatures for both wavelength bands and compared them, pixel by pixel, in scatter plots. Pixels belonging to quiet regions are clearly distinguished from those of faculae, where the brightness temperature at 1.55 μm is reduced systematically with respect to quiet regions, while pixels belonging to pores extend the cloud of facular pixels

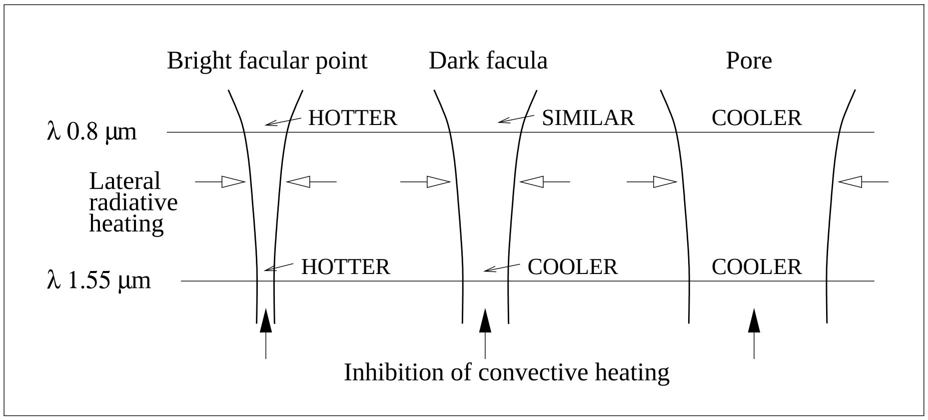

Figure 2.9: Schematic view of temperature conditions in magnetic features of different sizes (reprinted from Paper [11]).

smoothly toward low temperatures. The smooth transition between faculae and pores manifests a common magnetic origin of these features.

There are two basic mechanisms that determine the thermal structure of magnetic features: the inhibition of convective energy transport and lateral radiative heating, which depends on the size and internal density of the magnetic element. The second mechanism is more efficient in the upper photospheric layers, where the density is lower and the photon mean free path is greater than in the deep layers. In Fig. 2.9 we show a simplified comparison of the internal and external temperatures at the heights corresponding to the 0.80 and 1.55 μm continua for a small, medium and a large magnetic feature. In the smallest magnetic elements lateral radiative heating dominates and the elements appear to be brighter than their surroundings. These features, corresponding to bright facular points, are not detected in our infrared observations because they are below the resolution limit. Faculae, composed of magnetic elements of intermediate sizes, appear to be dark in the 1.55 μm band, because the lateral radiation is less efficient in their low layers and the effect of inhibition of convective energy transfer becomes to dominate. Since the faculae are nearly invisible at 0.80 μm, we can assume that in the high layers the lateral radiation still heats them to the temperature similar to that in their non-magnetic surroundings. Pores and sunspots are dark in both the visible and infrared because with further increase in the size of magnetic concentrations the efficiency of lateral radiative heating decreases and the effect of inhibition of convection becomes dominant at all heights throughout the photosphere.

The study of the centre-to-limb variation of the brightness temperatures and sizes of faculae (Sánchez Cuberes et al. 2002), which followed our Paper [11], has shown that the observed properties fit qualitatively with the predictions derived from the “hot wall” model of faculae (Spruit 1976; Knölker et al. 1985).

We have found that in most cases the pores are surrounded by “rings” of dark faculae. These rings demonstrate the presence of medium-size magnetic elements which reduce the temperature of the lowest photospheric layers (but not of the upper ones) outside the pore borders observed in the visible light. This confirms the finding that the magnetic radii of pores (and sunspots) are larger than their brightness radii (Keppens & Martínez Pillet 1996). An interesting question is to which magnetic and thermal conditions the transition from the medium-size magnetic elements in the ring to the large magnetic concentration of the pore corresponds. Observations relevant to this problem, however, require a much higher spatial resolution in the infrared than is available at present.

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Chapter 3

The papers

Herewith I state that my contribution to the following papers, published together with co-workers, is substantial. I proposed most of the research topics, participated in the most of observations (Papers [1–5] and [10–12]), contributed substantially to the data processing and analysis, and I am the first author of all the papers.

Michal Sobotka

Papers included in the dissertation

Research papers

[1] Sobotka M., Bonet J.A., Vázquez M.: 1992, *On the relation between the intensities of bright features and the local background in sunspot umbrae*, A&A 257, 757-762

[2] Sobotka M., Bonet J.A., Vázquez M.: 1992, *Spectroscopic determination of intensities of umbral bright features and adjacent background*, A&A 260, 437-440

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3.1 Paper 1

On the relation between the intensities of bright features and the local background in sunspot umbrae

M. Sobotka, J.A. Bonet, and M. Vázquez

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M. Sobotka, J.A. Bonet, and M. Vázquez

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3.3 Paper 3

A high resolution study of inhomogeneities in sunspot umbrae

M. Sobotka, J.A. Bonet, and M. Vázquez

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M. Sobotka, J.A. Bonet, M. Vázquez, and A. Hanslmeier

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M. Sobotka, P.N. Brandt, and G.W. Simon

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3.9 Paper 9

Fine structure in sunspots – IV. Penumbral grains in speckle reconstructed images

M. Sobotka and P. Sütterlin

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Temporal evolution of fine structures in and around solar pores

M. Sobotka, M. Vázquez, J.A. Bonet, A. Hanslmeier, and J. Hirzberger

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