Abstract

The 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 brief 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 of the dissertation 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.

About the dissertation

The 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.

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The 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.

The dissertation contains 12 original research papers published in refereed international journals and 2 review papers published in conference proceedings. These papers are marked by numbers in brackets to distinguish them from other references. Their list can be found at the end of this publication.

1 Introduction to the research topics

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 (spots without the penumbra) 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).

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 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 is 40° – 60° . Keppens & Martínez Pillet (1996) found that the magnetic field is extended beyond the visible radii of sunspots and pores. 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 corrected for stray light did not show any significant dependence of brightness on umbral size for large sunspots (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. 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 and Vázquez (1993). The decrease of umbral brightness with increasing umbral diameter was also obtained in Paper [3] from high-resolution white-light images and in Paper [11] from infrared images of pores.

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]. Two classes of them are the most important: (i) A sunspot (pore) is formed by a monolithic but inhomogeneous flux tube with magnetoconvection inside. In 3D non-linear numerical simulations of magnetoconvection in compressible fluid, fine 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). (ii) 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).

1.2 Sunspot fine structures

In many sunspots (see example in Fig. 1), instead of a single umbra, we observe multiple umbrae, which seem to behave like independent units. These are termed umbral cores, 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. We call it diffuse background. The well-distinguished darkest regions (local intensity minima) are called dark nuclei. The bright component is formed by umbral dots and by faint light bridges.

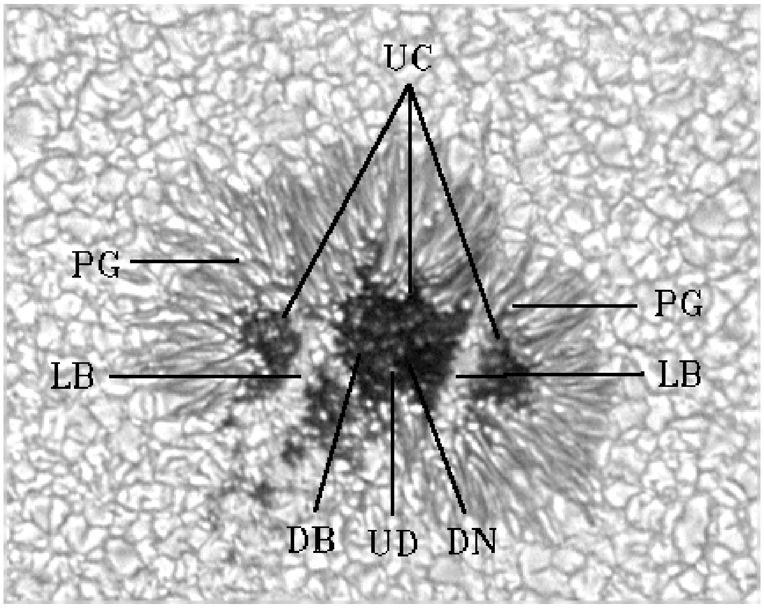

Figure 1: Illustration of basic fine-structure elements in sunspots: UC – umbral core, PG – penumbral grain, LB – light bridge, DB – diffuse background, UD – umbral dot, DN – dark nucleus (reprinted from Paper [13]).

Umbral dots are tiny bright point-like structures embedded in the umbral diffuse background (Danielson 1964). They appear in umbral cores as well as in pores. Excellent seeing and a telescope with resolution better than $0\farcs3$ are necessary to see them, often at the resolution limit. Observations of umbral dots are strongly influenced by image degradation caused by the telescope and seeing. Much effort has been devoted to determine temperatures, sizes, magnetic fields and velocities in umbral dots. Beckers & Schröter (1968) and Koutchmy & Adjabshirzadeh (1981) found that the colour temperatures and brightnesses of umbral dots are similar to those of the quiet photosphere and the diameters are of only 150–200 km. However, more recent observations indicate that the temperature and brightness vary in a broad range, mostly below the photospheric values (Grossmann-Doerth et al. 1986; Tritschler & Schmidt 1997, 2002; Papers [1], [2], [3], [7], [10], [12]). A moderate weakening (about 15 %) of magnetic field in umbral dots compared to the surrounding umbra was reported by Pahlke & Wiehr (1990), Wiehr & Degenhardt (1993) Schmidt & Balthasar (1994), Tritschler & Schmidt (1997) and Socas Navarro et al. (2004). Other authors (Buurman 1973; Zwaan et al. 1985; Lites et al. 1991) did not find any magnetic field reduction. The Doppler velocity measurements 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 deep-formed spectral line but less than 300 m/s in a line formed 300 km higher in the photosphere.

To interpret the discrepancies in magnetic field strength and velocities in umbral dots, 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 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 was present in the tube. With spectral lines formed at the top of the model, no magnetic field fluctuation can be seen. 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 this model were recently confirmed by Socas Navarro et al. (2004): Umbral dots are hotter than the surrounding umbra only in layers deeper than 100 km above $\tau = 1$. The magnetic field is weaker by 10 % than in the umbra and it is inclined to the normal. The inclination decreases with height, indicating a possible magnetic canopy (a "bottle neck") above the dot. We expect that 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.

Light bridges (Fig. 1) are bright elongated structures that separate umbral cores (strong light bridges) or are embedded in the umbra (faint light bridges). 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. 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), Rüedi et al. (1995) and Leka (1997) reported a higher inclination to the normal of the field vector. Recently, Jurčák et al. (2006) have shown that in light bridges the field strength increases and the inclination decreases with increasing height. This indicates the presence of a magnetic canopy above a deeply located weak-field region that forms the light bridge. 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). 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 develop into light bridges 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.

The sunspot penumbra is formed by bright and dark filaments. 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 (Fig. 1). 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 bright penumbral filaments (Scharmer et al. 2002). Muller (1973a) and Tönjes & Wöhl (1982) observed that penumbral grains move toward the umbra. In Papers [8] and [9] we found that most penumbral grains in the inner penumbra move toward the umbra while those in the outer penumbra move outwards. After reaching the penumbra-photosphere boundary, some outward-moving penumbral grains escape from the penumbra and penetrate into the surrounding granulation (Bonet et al. 2004).

Evershed (1909) discovered a wavelength shift and asymmetry of spectral lines formed in the penumbra. This effect is interpreted as a Doppler shift caused by a radial, nearly horizontal outflow across the penumbra. 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). 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.

It is very difficult to make a physical description of complex penumbral structures and their dynamics. 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. 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. This background field corresponds to the global magnetic field of the sunspot. The horizontal flux tubes are expected to conduct the Evershed flow. 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

Motions of magnetic structures, faculae and granules in the vicinity of pores and sunspots provide important information about the dynamics and evolution of active regions. Wang & Zirin (1992) reported converging flows around pores with speeds of 500 m/s and coherence scales of 2000–3000 km. In Paper [10] we came to the conclusion that the motions of granules in the vicinity of pores are driven by mesogranular flows. Another 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]. 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.

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 and the lateral radiative heating from the non-magnetic surroundings. 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. Infrared observations of dark faculae with spatial resolution better than $1''$ were made by Wang et al. (1998) and in Paper [11].

2 Principal results

2.1 Umbral dots

Around 1990, the idea of very small umbral dots 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. In Papers [1], [2], [3] and [12] we have studied the dependence of brightness of umbral dots on the brightness of the surrounding diffuse background.

In Paper [1], using white-light images with spatial resolution of about $0\overset{\prime\prime}{.}5$ acquired with the Gregory-Coudé Telescope on Tenerife, we found a linear dependence of brightnesses of 29 umbral dots 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 umbral dots. Using the continuum intensities calculated from the models, for the ratio of the umbral dot and background intensities (called a P/B ratio) we obtained the value 2.6 ± 0.2. These results were used by Degenhardt & Lites (1993b) to put observational constraints to their magnetohydrodynamical model of umbral dots. In Paper [3], we further measured the P/B ratio of 1507 umbral dots in white-light images and spectra, observed with the 0.5-m Swedish Vacuum Solar Telescope (SVST) on La Palma. The mean value of the observed P/B ratio was found to be 1.6 ± 0.3. In spite of a good spatial resolution ($0\farcs3$), 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 umbral dots (and 3 dark nuclei) from the observed Fe I 543.4 nm profiles. The ratio of the calculated umbral dot and background intensities was 3.3 ± 0.5. The measurements were repeated recently with the new 1-m Swedish Solar Telescope (SST), La Palma (Paper [12]). White-light images were taken simultaneously in two wavelength bands around 451 nm (blue) and 602 nm (red) with spatial resolution of $0\farcs15$. 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 umbral dots have "true" intensities higher than the quiet photosphere and the "true" P/B ratio is 4 ± 2 (blue) and 3 ± 2 (red).

The dependence of the umbral dot brightness on the brightness of the adjacent diffuse background 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 umbral dots 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 umbral dots.

Temporal variations of umbral dots brightness were studied in Paper [7]. The power-spectrum analysis revealed several periods, among them 32 and 16 minutes. The temporal variations of brightness and size were utilized by Hamedivafa & Sobotka (2004) to check for the Joule heating mechanism in umbral dots.

Observed *sizes* (diameters) of umbral dots are always influenced by the finite resolution of the telescope and by the seeing. Thus the "true" sizes of umbral dots 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. In Paper [3], using the relation between the umbral dot 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 umbral dots are uncorrelated. In 1995 we have developed a feature tracking code (Paper [6]) to detect small-scale features and to record their evolution in time. This procedure returns intensities, sizes, lifetimes and positions of umbral dots that are not biased by observer's subjective selection. Observed diameters of 11758 umbral dots, 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 did not show any "typical" value. In fact, the number of umbral dots strongly increased with decreasing size down to the resolution limit. This result was later confirmed by Tritschler & Schmidt (2002). 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 to nearly $0\farcs1$. In Paper [12] we used the new 1-m SST to measure sizes of umbral dots in two sunspots and two pores with spatial resolution better than $0\farcs15$. Histograms of observed diameters of umbral dots, 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 umbral dots are spatially resolved by a 1-m telescope. The average "true" diameter computed for 585 umbral dots 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.

Lifetimes of umbral dots 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 umbral dots 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 umbral dots 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 umbral dots had lifetimes shorter than 10 minutes, 27 % between 10 and 40 minutes, 6 % between 40 and 120 minutes and 1 % of umbral dots existed longer than 2 h. We did not find any "typical" value; rather, the shorter the lifetime, the more numerous umbral dots. This result differs from the former estimates, which were based on observations of small samples of umbral dots and probably influenced by visual selection effects and intensity variations of long-lived umbral dots.

The *spatial distribution* of umbral dots is an important observational input to theoretical models. Umbral dots can be found everywhere in the umbra (e.g. Adjabshirzadeh & Koutchmy 1980). Their distribution, however, is not uniform. They form clusters and alignments at some "preferred" locations in the umbra and they are almost missing in dark nuclei. From measurements in 18 different umbral cores we found that the average nearest neighbour distance of umbral dots ($0\farcs5$–$0\farcs75$) decreases and the observed filling factor (the relative area occupied by umbral dots, 6 %–15 %) increases with increasing brightness of the diffuse background (Paper [3]). Observing with the 1-m SST (Paper [12]), we obtained the average nearest neighbour distance in the range $0\farcs38$–$0\farcs48$ and the mean filling factor (based on observed areas) equal to 9 %. 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 ($d > 0\overset{\prime\prime}{.}4$) and long-lived ($t > 40$ minutes) umbral dots tend to appear in relatively bright regions of the diffuse background (Paper [6]), where the magnetic field strength is locally weaker. The brightest umbral dots are usually located at the periphery of the umbra (Paper [7]), where the diffuse-background intensities are high.

An often discussed question was if umbral dots 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 umbral dots*. We have studied this problem in Paper [3] and derived from our data the contribution of umbral dots 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 umbral dots generate about 10% and in the bright ones 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 umbral dots below the visible surface, umbrae strongly populated by dots could have brighter diffuse background than the less populated ones.

Time series of high-resolution white-light images make it possible to measure *horizontal motions* of umbral dots. Ewell (1992), Wang & Zirin (1992) and Molowny-Horas (1994) reported that some umbral dots, perhaps associated with penumbral grains, move inwards, toward the centre of the umbra. In Paper [5] we analyzed a 51 minutes long series of images, acquired at the 0.5-m SVST. The horizontal motions of umbral and penumbral fine structures were determined by applying the method of local correlation tracking (LCT), described by November & Simon (1988). Penumbral grains moving towards the umbra sometimes crossed the penumbra-umbra boundary, became peripheral umbral dots and moved farther into the umbra until they met dark nuclei. Then, they slowed down and disappeared. In some cases, the "collision" of umbral dot with a dark nucleus was accompanied by a brightening of another umbral dot, already existing 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 (Paper [7]). We suggested that dark nuclei are dominant structures in the umbra, influencing strongly the motion of umbral dots. Horizontal motions of umbral dots were further studied in Paper [7], applying our feature-tracking code to the 4.5-h series acquired with the 0.5-m SVST. The number of umbral dots decreases with increasing magnitude of the horizontal motion velocity and the velocity magnitude decreases with increasing lifetime of umbral dots. Speeds of umbral dots are grouped at 100 and 400 m/s. Umbral dots are on the average faster at the periphery of the umbra than in the central region but one can find "fast" and "slow" umbral dots in all parts of the umbra.

In general, horizontal motions of umbral dots are apparent, i.e., they may not represent a real mass motion. Thomas & Weiss (2004) suggested that we probably observe a wavelike translation of the convective pattern, which is halted by the stronger, more vertical magnetic field in the dark nuclei. Another possibility is, in case of the cluster model, a motion of intersections with the visible surface of the columns with hot field-free plasma.

Solar pores show the same variety of fine-scale features like sunspot umbrae – umbral dots, light bridges and dark nuclei. The first detailed photometry of *umbral dots in pores* was done by Bonet et al. (1995). In Paper [10], we identified and tracked the evolution of 171 umbral dots that appeared in a large pore (diameter $8''.9$) during a 67 minute time series acquired with the 0.5-m SVST. Umbral dots 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 forming process of umbral dots is stronger and more stable in weaker magnetic field of pores than in strong field of developed umbrae.

We have already mentioned that some penumbral grains penetrate into the sunspot umbra and are observed as inward-moving umbral dots. 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 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.

The results presented above 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).

2.2 Light bridges

Several attempts were made to establish a morphological classification of light bridges (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 classification based on two parameters: (i) The morphology related to the sunspot configuration, namely, if light bridge separates umbral cores (strong light bridge) or not (faint light bridge). (ii) The internal structure – granular or filamentary. Thus, four basic types of light bridges 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 light bridges in the general configuration of the umbra, while the second characterizes the inclination of magnetic field (less inclined in granular light bridges, more inclined in filamentary ones). 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]. They 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 inside the bridge is of about 0.5, close to the fractional area granule-intergranule in the quiet photosphere. Two FG bridges were also observed in a large pore (Paper [10]). A photometric and spectroscopic study of two SG bridges was published in Paper [4]. The data were acquired at SVST 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 the bridges, with a mean nearest-neighbour distance of $0''.5$. 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.

2.3 Penumbral grains

Penumbral grains 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 penumbral grains toward the umbra. 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 penumbral grains (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 penumbral grains was studied in this case (Paper [9]). Our results were used by Schlichenmaier (2002) to improve the moving tube model.

The *horizontal motions* of penumbral grains were determined from the positions tracked in time and smoothed by cubic splines. Of the 469 penumbral grains, analyzed in Paper [8], 73 % moved inward toward the umbra (we label them INW), while 27 % moved outward toward the photosphere (we call them OUT). Of the 1058 penumbral grains, analyzed in Paper [9], 54 % moved inward and 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 penumbral grains are of type OUT; inside most are INW. The time-averaged horizontal velocities are typically 400 m/s for INW penumbral grains and 500 m/s for OUT ones. The velocities depend on the radial position in the penumbra. For INW penumbral grains 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 penumbral grains 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 penumbral grains 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 penumbral grains 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), penumbral grains 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 penumbral grains 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.

Lifetimes of penumbral grains were first measured by Muller (1973a,b) and Tönjes & Wöhl (1982). They obtained 1–3 h with the maximum in the middle part of the penumbra. In Paper [8] we show that the number of penumbral grains increases with decreasing lifetime. For INW penumbral grains observed during the 4.5 h time series the maximum lifetime is almost 4 h but only 17 % live longer than 1 h; the mean lifetime is 39 minutes. The lifetimes 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 penumbral grains are shorter compared to the INW ones and show only little variations with the position. The maximum and mean values are 59 and 25 minutes. 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 penumbral grains (automated versus visual), is discussed in Paper [8]. We are convinced that our statistics are significantly better.

2.4 Photosphere in active regions

In Paper [10] we employed the LCT technique to analyze the *horizontal motions of granules* around five small and one large (diameter $8''.9$) pore. In all flow maps we see the typical divergent "rosetta" velocity patterns characteristic of mesogranulation (Fig. 2). 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 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

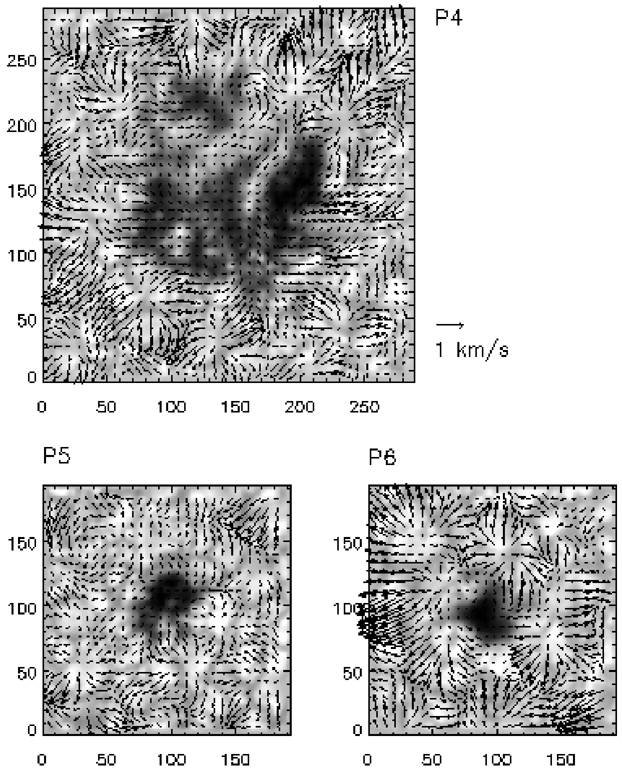

Figure 2: Maps of horizontal motions around pores. The coordinate unit is 1 pixel, i.e., 0″.062 (reprinted from Paper [10]).

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.

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

Two basic mechanisms 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 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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