PHOTOSPHERIC LAYERS OF SUNSPOTS AND PORES

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ABSTRACT

Sunspots and pores appear as a consequence of interactions between strong magnetic fields and moving plasma. A wide variety of small-scale features, presumably of convective origin, are observed in photospheric layers of sunspots and pores: Umbral dots, light bridges, penumbral filaments, and penumbral grains. Each type of features has specific morphological, photometric, spectral, and kinematic characteristics due to a broad range of magnetic field strengths and inclinations in umbrae and penumbrae. Spots and pores modify velocity fields in adjacent photosphere and subphotospheric layers. Recent high-resolution spectral, broad-band, and helioseismic observations of the structure, dynamics, and magnetic fields of sunspots and pores, together with theoretical interpretations, are discussed in this review.

1. INTRODUCTION

This review attempts to summarize recent results of observations, together with relevant theoretical models, published mostly in the past decade. It can be considered as a continuation and extension of previous reviews (Sobotka 1997, 1999). In those papers the reader could find more basic information and earlier data related to the topic.

Solar activity is a complex interplay between magnetic fields and plasma motions, driven mostly by solar convection and differential rotation. If the magnetic field inhibits the convective transfer of heat in a sufficiently large volume, a sunspot or a pore appears. They are the easiest-to-observe phenomena of solar activity – largest sunspots can be seen even by naked eye.

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. Two classes of theoretical models have been developed to describe the structure of sunspots and pores:

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 appear structures similar to the observed ones: 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, possibly, faint 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 (see Sect. 6).

2. SUNSPOTS, PORES, AND THEIR FORMATION

We distinguish between sunspots and pores simply on the basis of the presence of a penumbra: Sunspots have the penumbra while pores do not. In case of young and irregular spots, often only some sectors of the penumbra are developed. Near large pores, some transient filamentary structures resembling penumbra can be observed. These structures, however, are small and unstable.

Typical values of several important parameters of sunspots and pores are summarized in Table 1: Visible diameter (including penumbra) D_{vis} in white light, minimum umbral intensity I_{min} in units of the mean photospheric intensity I_{ph}, magnetic field strengths $B(0)$ and $B(R_{vis})$ in the center of the umbra and at the visible boundary with the photospheric granulation, and magnetic field inclination $\gamma(R_{vis})$ at this boundary. These data were taken from the papers by Martínez Pillet (1997), Sütterlin (1998) and Keil et al. (1999). We have to note that magnetic field strengths and inclinations observed in individual sunspots and pores show a cosiderable scatter and may differ substantially from the values presented below.

Table 1. Typical parameters of sunspots and pores (see text for explanation).

Parameter	Pores	Sunspots
D_{vis} (Mm)	$1-6$	$6-40$
I_{min} ($I_{ph}=1$)	$0.2-0.7$	$0.05-0.3$
$B(0)$ (G)	1700	3000
$B(R_{vis})$ (G)	1200	800
$\gamma(R_{vis})$	$40^\circ-60^\circ$	$\sim 70^\circ$

An important question is how the minimum intensity and the magnetic field strength in the umbra depend on the size D_{vis}. Since this problem is discussed in detail by Sobotka (1999), only a brief summary is given here. Observations corrected for stray light originating in the terrestrial atmosphere show that the minimum intensity decreases and the magnetic field strength increases with increasing D_{vis} in all pores and in sunspots with umbral diameters smaller than 6 Mm. The scattering of the values, however, does not allow to establish a clear relationship. In large spots with umbral diameters exceeding 6 Mm, the dependence of I_{min} and B on D_{vis} is not observed.

Keppens & Martínez Pillet (1996) found that the magnetic field of sunspots and pores is extended beyond D_{vis} in the form of a canopy, so that the "magnetic radius" is larger than D_{vis} by factor of about 1.3.

How a pore can develop into a sunspot, forming a penumbra? As the magnetic flux increases inside the pore, the field becomes more inclined at the edge of the pore. The magnetic configuration becomes unstable and the interaction of strongly inclined field with the surrounding convective motions can cause the formation of a penumbra (see Keil et al. 1999 for details and references).

The observations (e.g. Wang & Zirin 1992, Keil et al. 1999) show that sunspots and pores are formed by merging of small magnetic elements, motions of which are driven by supergranular and subsurface flows. 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.

Very high spatial resolution is necessary to observe small-scale features in the umbra and penumbra, and the structure of light bridges. Contemporary observations take advantage of 2D spectroscopy and spectral-line inversion methods to study thermal structure, magnetic field, and line-of-sight velocities, while feature tracking techniques are used to investigate horizontal motions and temporal evolution.

3. UMBRAL FINE STRUCTURES

3.1. Umbral dots

Tiny bright features, just at the limit of resolution of large solar telescopes, are seen in umbrae of sunspots and pores. Their apparent *brightness* range from 0.2 to 0.7 I_{ph} at $\lambda \simeq 4500$Å. The histogram of brightnesses shows two peaks that may correspond to two populations of umbral dots (Sobotka et al. 1997b, Tritschler & Schmidt 2002). The less bright dots are mostly located in central parts of an umbra, while the brighter ones are concetrated at the periphery.

The dark umbral background is not uniform in intensity – it contains brighter and darker regions with diffuse transitions and its brightness increases toward the umbral border. We can ask therefore, if the intensity of umbral dots is related to the intensity of the backgroud. Several observations (e.g. Sobotka et al. 1993, Denker 1998, Tritschler & Schmidt 2002) show that it is very probable. The observed intensities I_{ud} of umbral dots are correlated to the local background intensities I_b and, on average, $I_{ud} \simeq 1.3$–$1.5\ I_b$. Since umbral dots are mostly unresolved features, their real intensities are higher. From spectroscopic measurements Sobotka et al. (1993) derived a relation $I_{ud} \simeq 3\ I_b$, which was confirmed later by Sütterlin & Wiehr (1998).

Observed *sizes* of umbral dots range from $0.''2$ to $0.''8$, but features larger than about $0.''6$ correspond rather to clusters of umbral dots than to single ones. The histogram of observed sizes does not show any "typical" value. In fact, the number of umbral dots strongly increases with decreasing size down to the resolution limit (Sobotka et al. 1997a). Due to limited spatial resolution, observed sizes are larger than real ones. Using the phase-diversity technique, Tritschler & Schmidt (2002) 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 $D = 70$ cm telescope. The histogram of corrected sizes showed the same shape like that of the observed ones and the average corrected diameter was only by $0''.02$ smaller than the mean observed diameter. These facts imply that most of umbral dots remained unresolved and that much larger telescopes are needed to measure their real sizes and brightnesses.

The range of *lifetimes* of umbral dots is broad: Two thirds of dots live less than 10 minutes, 27 % has lifetimes between 10 and 40 minutes, and only 1 % live longer than 2 hours (Sobotka et al. 1997a). Long-lived umbral dots show quasi-periodic intensity fluctuations with intervals of about 30 minutes.

Umbral dots are observed to *move horizontally* within the umbra with speeds from 0 to 800 m/s. On average, dots are faster in peripheral parts of the umbra, where motions toward the umbral center are often observed. Some umbral dots may arise from inward moving penumbral grains that crossed the penumbra/umbra boundary.

Umbral dots are present everywhere in the umbra but their *spatial distribution* is not uniform. They form clusters and alignments at some preferred locations (mostly at the interstices of fragments) and they are almost missing in dark nuclei. The nearest-neighbour distance of umbral dots ($0''.5$–$0''.75$) decreases and the observed filling factor (the relative area occupied by dots, 6–15 %) increases with increasing brightness of the umbral background.

These facts might give rise to a question if the umbra is heated by umbral dots. If so, this could be a possible explanation of the relation between the intensities I_{ud} and I_b. Sobotka et al. (1993) estimated that at the visible surface, umbral dots contribute by only 10–20 % of the total radiative flux, so that the umbral brightness is influenced mainly by the brightness of the background. However, we cannot exclude that the umbral background can be heated by lateral radiation from umbral dots below the visible surface.

Accepting the idea that umbral dots are manifestations of magnetoconvection or of penetrating columns of hot field-free gas, we can expect that their *magnetic field* is reduced and their *line-of sight velocities* are directed upwards. However, no significant fluctuations of magnetic and velocity fields spatially correlated with umbral dots were observed. Some indications of upflows of about 50 m/s (Rimmele 1997) and a slight reduction of magnetic field strength (e.g Schmidt & Balthasar 1994) were found, but on spatial scales larger than $1''$, corresponding to clusters of umbral dots or to possible fluctuations in umbral background. The problem of magnetic and Doppler "invisibility" of umbral dots can be explained assuming that dots are deep-formed structures visible in continuum but with very weak signatures at the heights where spectral lines are formed (Degenhardt & Lites 1993a,b).

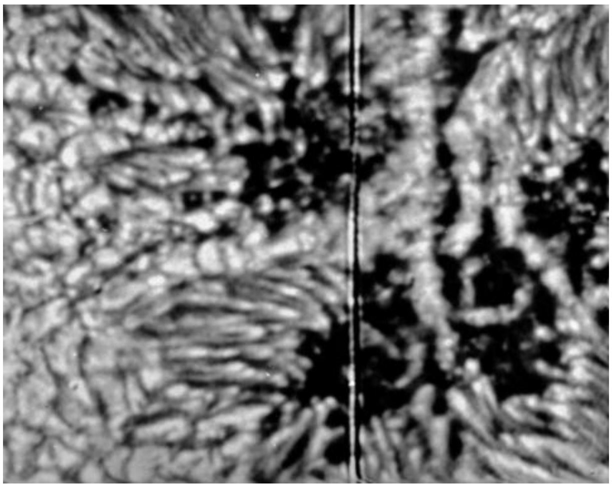

Figure 1. Granular light bridges in sunspot NOAA 6709 (slit-jaw image, Swedish Vacuum Solar Telescope, La Palma).

A recent attempt to obtain thermal, magnetic, and velocity parameters of umbral dots has been made by Socas Navarro (2002). From the inversion of Stokes profiles observed with La Palma Solar Polarimeter it was found that an umbral dot is 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 at all heights and it is inclined 30°–40° to the normal. The inclination decreases with height, indicating a possible magnetic canopy above the dot. Upflow of about 200 m/s was detected. It is necessary to do such measurements for many different umbral dots to get conclusive results.

3.2. Light bridges

Light bridges (Fig. 1) are bright elongated structures that separate umbral cores or are embedded in the umbra (see Sobotka 1997 for a 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.

Many observations confirm that *magnetic field* in light bridges is much weaker compared to the umbra. For example, Leka (1997) reports that it is reduced by 500–1200 G and more inclined to the normal than in the srrounding umbra (but less than in the penumbra). This inclination is explained by existence of magnetic canopies above light bridges. *Line-of-sight* *velocities* show upflows and downflows with magnitudes up to 400 m/s, indicating convective motions.

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. 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.

4. PENUMBRAL FINE STRUCTURES

4.1. Penumbral filaments

The most typical feature of penumbral fine structures is the elongated shape, a consequence of the strongly inclined magnetic field. Bright (about 1 I_{ph} on average) and dark (0.6 I_{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, in the sense that a local intensity maximum can be less bright than a minimum elsewhere.

The *width* of penumbral filaments is still under discussion. Spatial power spectra presented by Sánchez Almeida & Bonet (1998) indicate that the noise level is not reached at their resolution limit of $0''.28$, so that penumbral filaments are in fact unresolved features. On the other hand, Balthasar et al. (2001) derived from comparison of observed pover spectrum with model calculations a typical width of 250 km ($0''.35$).

Important questions are, how the strength and inclination of *magnetic field* differ between bright and dark filaments and if the *Evershed flow*, an almost horizontal outflow of 3–4 km/s dominating the velocity field in the penumbra, is confined to dark or bright filaments. These problems are difficult to solve for two reasons: Magnetic-sensitive lines are formed higher than the continuum and a very high spatial resolution in the spectrum is required. A significant effort is dedicated to solve these problems but results of observations are often confusing. Recent works converge to the following points:

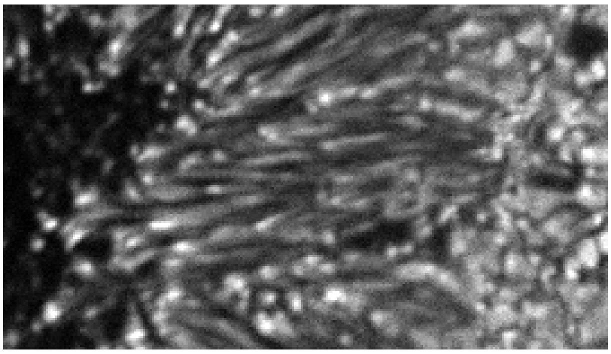

Figure 2. Penumbral grains in sunspot NOAA 8580 (Swedish Vacuum Solar Telescope, La Palma).

1. Dark filaments host stronger and more inclined magnetic field as compared to that in bright filaments (e.g. Wiehr 2000, Westendorp Plaza et al. 2001).
2. Evershed flow tends to be concentrated in dark filaments, but it is also present in the bright ones. Its velocity decreases and its spatial structure becomes more diffuse with increasing height in the penumbra (e.g. Rouppe van der Voort 2002). Upflows are observed near the umbra-penumbra border and downflows near the penumbra-granulation border (Hirzberger & Kneer 2001).

4.2. Penumbral grains

Bright penumbral filaments consist of penumbral grains, elongated comet-like features (Fig. 2). Their brightness range from 0.84 to 1.10 I_{ph}, their width is of about $0''.5$, and length between $0''.6$ and $3''.7$.

Horizontal motions and *lifetimes* of penumbral grains were measured from time series of high-resolution images (Sobotka et al. 1999a, Sobotka & Sütterlin 2001). In the inner penumbra, up to 0.6–0.7 of the distance from the umbra to the photosphere, they move mostly inwards toward the umbra with typical speed of 500 m/s, in the outer penumbra their motion is directed mostly outwards with speed 750 m/s. In total, 54 % of all penumbral grains show inward motion and their mean lifetime is 40 minutes. The outward-moving penumbral grains live 25 minutes on average.

Outward-moving penumbral grains near the penumbra-granulation boundary evolve in three possible ways (Sobotka et al. 2002): About 2/3 of them disappear in the penumbra before reaching the boundary, 1/6 cross the boundary and convert into small (diameter $< 0''.5$) bright features, and about 1/6 cross the boundary, expand in size, and develop into granules. All the features that cross

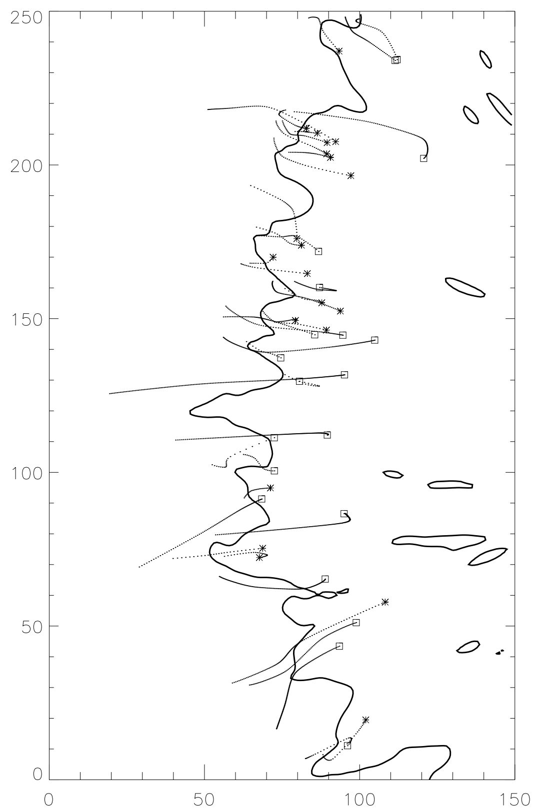

Figure 3. Trajectories of penumbral grains that crossed the penumbra-granulation boundary. Origins of trajectories are marked by asteriscs for small features and by squares for granules.

the penumbra-granulation boundary preserve their outward motion with average speeds of 1.4 km/s (small features) or 1.1 km/s (granules). An example of their trajectories is plotted in Fig. 3.

This direct relation between the outward-moving penumbral grains and granulation points to a complex interaction of subphotospheric convection with the nearly horizontal magnetic field of the penumbra and to the heat exchange along the outer penumbral boundary in the subphotospheric layers, as proposed by Jahn & Schmidt (1994).

4.3. Penumbral models

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 future development.

The *uncombed penumbral model* was suggested by Solanki & Montavon (1993) to explain broad-band circular polarization in sunspots. 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. 4). This background field corresponds to the global magnetic field of the sunspot. Field strengths in both systems of magnetic field are model parameters – they 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 downward directed component. The approximation of penumbral structure based on the uncombed model is still developing, taking advantage of inversion methods applied to polarimetric measurements.

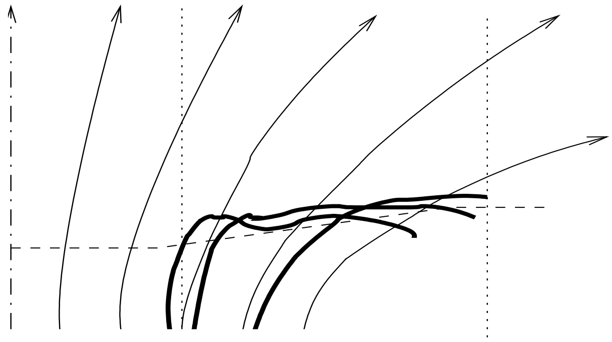

Figure 4. A scheme of uncombed penumbral model. Borders of umbra and penumbra are marked by dots, the visible surface by dashes. Solid lines represent two systems of magnetic field.

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 has to be further developed to include the interaction of many flux tubes with different inclinations and to explain the existence of outward-moving penumbral grains.

5. HORIZONTAL MOTIONS AROUND SUNSPOTS AND PORES

The column of cold gas forming a sunspot or a pore interacts with convective motions in the surrounding convection zone. This fact is important from the point of view of the stability of sunspots and pores. The horizontal flow patterns, derived by local correlation techniques from broad-band intensity movies with high spatial resolution, are different for sunspots and pores:

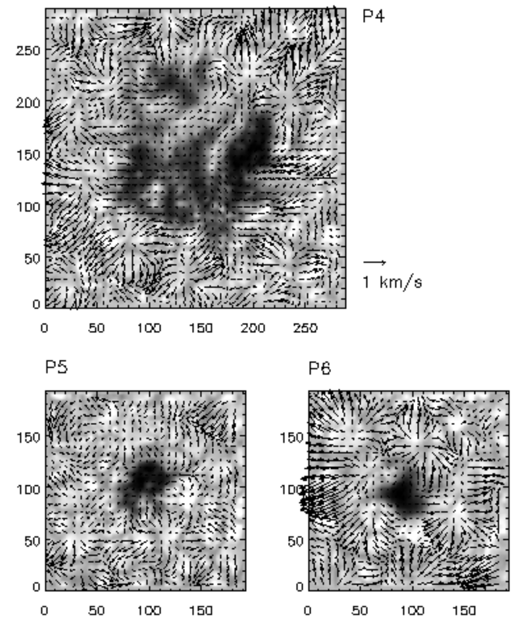

Figure 5. Maps of horizontal flows around pores. The coordinate unit is 0″.062 (Sobotka et al. 1999b).

Pores: Granular motions in the vicinity of pores are driven by centers of diverging local horizontal motions, seen as "rosettas" of horizontal velocity vectors in flow maps (Fig. 5). The divergence centers are manifestations of exploding granules and mesogranular flows. Motions toward the pores dominate in a 1500 km (2″) wide zone around the pore boundary, while at larger distances the granules move away from the pores. Pushed by these motions, small granules and granular fragments located close to the pore border sometimes penetrate into the pore, where they move inward as bright short-lived features very similar to umbral dots (Sobotka et al. 1999b, Roudier et al. 2002).

Sunspots: In broad-band intensity movies it can be observed that granules move away from the penumbral border. Numerous divergence centers (rosettas) with average size of 3″, caused by exploding granules and mesogranular flows, are present in granulation outside a sunspot. Rosettas adjacent to the penumbra are asymmetric, because the motions directed into the sunspot are suppressed. The velocities inside rosettas are approximately 600–700 m/s and they are slightly reduced within the magnetic radius of the spot (Sobotka et al. 2002).

Divergence centers themselves move away from the spot in radial directions. A flow map derived from a series of 24 images of divergence fluctuations, lasting 2 hours, is shown in Fig. 6. These motions with average speed of 500 m/s are observed in a limited zone around the sunspot (a moat). The width of the moat is comparable with that of the penumbra. It can be concluded that the radial outflow away from the spot does not act only on individual granules but also on larger dynamical systems like exploding granules and mesogranules.

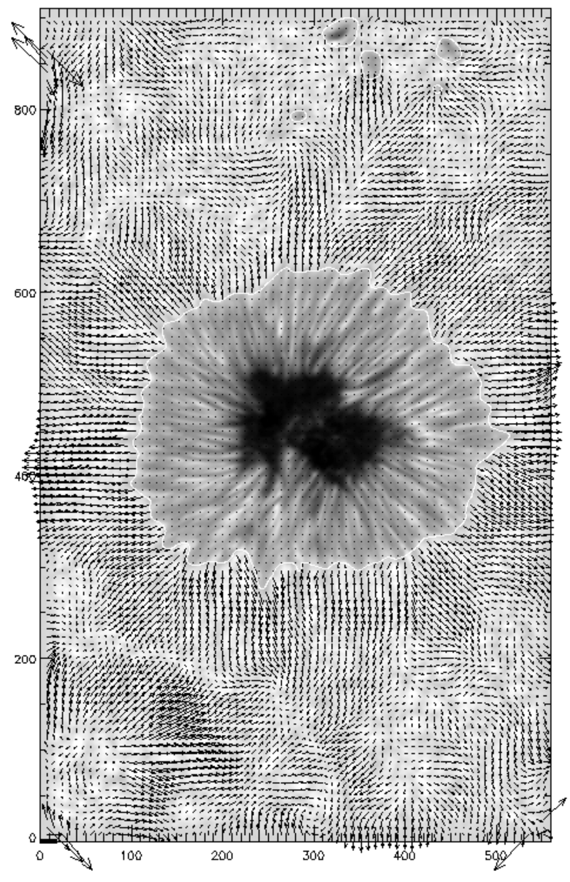

Figure 6. Map of horizontal velocities of divergence fluctuations, showing an outflow in the sunspot moat (Sobotka et al. 2002). The coordinate unit is 0″.083. The length of the black bar at coordinates (0,0) corresponds to the velocity magnitude of 1 km/s.

6. MOTIONS IN SUBPHOTOSPHERIC LAYERS

6.1. Results of local helioseismology

The time-distance technique in helioseismology is based on measuring travel times of acoustic waves (p-modes) between different points on the solar surface. On the basis of high-resolution dopplergrams, obtained from the SOHO/MDI instrument, the time-distance technique produces 3D tomographic maps of subphotospheric temperature inhomogeneities, magnetic fields, and flows.

Zhao et al. (2001) inferred mass flows in and around a sunspot below the solar surface. Strong converging and downward-directed flows are detected below the sunspot at a depth of 1.5 to 5 Mm. These flows disappear below 5 Mm, which is also the approximate depth where the temperatures inside and outside the sunspot become equal. So it may be interpreted that the converging and downward flows are related to the sunspot's thermal properties and that the sunspot, as defined by its thermal and hydrodynamic signatures, is a relatively shallow phenomenon with a depth of 5–6 Mm. In deeper layers, 6–10 Mm below the visible surface, powerful outflows which extend horizontally more than 30 Mm are found together with an upflow beneath the sunspot. A strong mass flow across the sunspot is detected at a depth of 9–12 Mm.

The converging and downward motions beneath the sunspot cannot immediately be consistent with surface motions observed spectroscopically, in particular with the diverging Evershed flow. Gizon et al. (2000) used surface gravity waves to probe flows in a shallow region from the surface to a depth of 2 Mm. They detected a radial outflow up to 1 km/s from the spot center, consistent with the Evershed and moat outflows. The velocities are systematically lower than those at the surface, suggesting that the Evershed flow is a shallow phenomenon. It is not straightforward to reconcile these findings with the converging flows found by Zhao et al. (2001) and more work has to be done in this direction.

6.2. Monolithic or cluster model of a sunspot?

We have seen in all the previous paragraphs that observations do not give a clear hint which of the basic models of sunspots and pores – the monolithic flux tube with magnetoconvection or the cluster of isolated flux tubes – corresponds better to the reality. Light bridges, umbral dots, and penumbral grains can be interpreted as manifestations of magnetoconvection in inhomogeneous magnetic field. But what causes the inhomogeneities? Is it the intrinsic cluster structure of magnetic field or is it a result of powerful magnetoconvective processes? Surface observations did not give an answer yet.

Converging and downward motions in subphotospheric regions around sunspots, discovered by time-distance helioseismology, were predicted by both models. The cluster model requires downdrafts and converging flows below the sunspot to hold together the flux tubes (Parker 1979a). On the other hand, numerical experiments on monolithic flux tubes in a compressible convecting atmosphere (Hurlburt & Rucklidge 2000) also show subphotospheric motions of this type. The results of simulations are in a good agreement with observations presented in Sect. 5. Flows around fluxtubes are driven by cooling of plasma near the fluxtube, leading to downflows around the tube and hence inflows at the visible surface. Such motions are observed around pores. The situation with sunspots is different, because the outflow is observed in the moat. Hurlburt & Rucklidge propose that the downward and inward flows are hidden beneath the inclined edge of a large flux tube – the penumbra. Thus, only a distant cell providing the outflow at the surface is visible (Fig. 7).

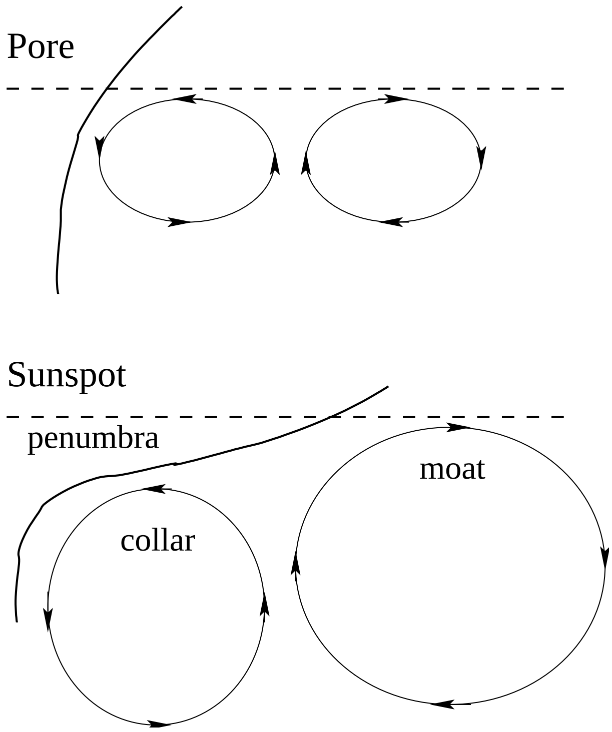

Figure 7. A sketch of the flows around a pore and a sunspot, according to Hurlburt & Rucklidge (2000).

At present it seems that even the probing of deep layers has not decided which model is more realistic. Nevertheless, there is an exception: The observation of the transverse flow across the sunspot at a depth of 9–12 Mm (Zhao et al. 2001) indicates that the cluster model, permeable for such motions, could be more suitable in this case.

ACKNOWLEDGMENTS

This work was supported by the Grant Agency (Grant A3003903) and by the Key Project (K2043105) of the Academy of Sciences of the Czech Republic.

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