SOLAR DYNAMICS AND ITS EFFECTS ON THE HELIOSPHERE AND EARTH

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SOLAR DYNAMICS AND ITS EFFECTS ON THE HELIOSPHERE AND EARTH

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FOREWORD

The SOHO and Cluster missions form a single ESA cornerstone. Yet they observe very different regions in our solar system: the solar atmosphere on one hand and the Earth's magnetosphere on the other. At the same time the Ulysses mission provides observations in the third dimension of the heliosphere, and many others add to the picture from the Lagrangian point L1 to the edge of the heliosphere. It was our aim to tie these observations together in addressing the topic of Solar Dynamics and its Effects on the Heliosphere and Earth with a workshop at the International Space Science Institute (ISSI), under the auspices of the International Living With a Star (ILWS) program. It started out with an assessment and description of the reasons for solar dynamics and how it couples into the heliosphere. The three subsequent sections were each devoted to following one chain of events from the Sun all the way to the Earth's magnetosphere and ionosphere: The normal solar wind chain, the chain associated with coronal mass ejections, and the solar energetic particles chain. The final section was devoted to common physical processes occurring both at the Sun and in the magnetosphere such as reconnection, shock acceleration, dipolarisation of magnetic field, and others.

This volume is the result of an ISSI Workshop held in April 2005. An international group of about forty experimenters, ground-based observers, and theoreticians was invited to present and debate their data, models, and theories in an informal setting. The group was convened by Madhulika Guhathakurta (NASA HQ), Gerhard Haerendel (then at IU Bremen), Hermann Opgenoorth (ESA-ESTEC), Roger M. Bonnet, Götz Paschmann, and Rudolf von Steiger (all ISSI).

It is a pleasure to thank all those who have contributed to this volume and to the workshops in general. First of all, we thank the authors for writing up their contributions. All papers were peer-reviewed by referees, and we thank the reviewers for their critical reports. We also thank the directorate and staff of ISSI for selecting this topic for a workshop and for their support in making it happen, in particular Roger M. Bonnet, Brigitte Fasler, Vittorio Manno, Saliba F. Saliba, Irmela Schweizer, and Silvia Wenger.

December 2006

D. N. Baker, B. Klecker, S. J. Schwartz, R. Schwenn and R. von Steiger

Group photograph; from left to right (nose tip counts): Markus Aschwanden, Rainer Schwenn, Hannu Koskinen, Hermann Opgenoorth, Alexander Kosovichev, Peter Cargill, Mark Lester, Ester Antonucci, John Leibacher, Rudolf von Steiger, Steve Schwartz, Joachim Birn, Rumi Nakamura, Dan Baker, Mihir Desai, Roger-Maurice Bonnet, Lika Guhathakurta, Sarah Gibson, Thomas Zurbuchen, Silvia Wenger, Berndt Klecker, Jerry Goldstein, Brigitte Fasler, Yannis Daglis, Richard Mewaldt, Jon Linker, Götz Paschmann, Ruth Esser, Jörg Büchner, Bob Lin, Dave Sibeck, Joe Giacalone, Nat Gopalswamy, Bernhard Fleck, Mike Wiltberger, Gerhard Haerendel (picture taken by Stein Haaland).

ACTIVE REGION DYNAMICS
Recent Helioseismology Results

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Abstract. New methods of local helioseismology and uninterrupted time series of solar oscillation data from the Solar and Heliospheric Observatory (SOHO) have led to a major advance in our understanding of the structure and dynamics of active regions in the subsurface layers. The initial results show that large active regions are formed by repeated magnetic flux emergence from the deep interior, and that their roots are at least 50 Mm deep. The active regions change the temperature structure and flow dynamics of the upper convection zone, forming large circulation cells of converging flows. The helioseismic observations also indicate that the processes of magnetic energy release, flares and coronal mass ejections, might be associated with strong (1–2 km/s) shearing flows, 4–6 Mm below the surface.

Keywords: Sun: activity, Sun: heliseismology, Sun: interior, Sun: magnetic field, sunspots

1. Introduction

Active regions are the most important source of heliospheric disturbances. They are formed by magnetic fields generated by dynamos in the convection zone and emerging from the Sun's interior. Magnetic field topology and magnetic stresses in the solar atmosphere are likely be controlled by motions of magnetic flux footpoints in the sub-photosphere. However, the depth of these motions is unknown. Twisting and shearing of the magnetic field of active regions by subphotospheric motions as well as its interaction with new emerging magnetic field result in flares and CMEs. Helioseismology provides tools for diagnosing the subsurface structures and dynamics, and allows us to investigate the origin of solar magnetic fields, formation and evolution of active regions, the relationship between the internal dynamics and activity, and to develop methods for predicting the emergence and evolution of active regions and their activity. The helioseismic investigation of the dynamics of active regions has only just begun, and the results are still very preliminary. However, we are beginning to develop a new understanding of the lifecycle of active regions, their emergence, evolution and decay, as well as the relationship between their activity and internal dynamics. Specifically, some of the questions that are studied by local helioseismology are:

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- How deep are the roots of sunspots and active regions?
- How fast do active regions emerge?
- What is the basic mechanism of formation of active regions: are they formed by a large magnetic Ω-loop breaking into smaller parts near the surface, or by merging together fragmented small-scale magnetic structures in the subphotospheric layers?
- Why do active regions tend to appear in the same place forming long-living complexes of activity ('active longitudes')?
- How are the twisted ('δ-type') magnetic configurations, which produce the most energetic flares and CMEs, formed?
- How can surface and subsurface plasma flows affect stability and magnetic energy release of active regions?
- How do sunspots and active regions decay?
- What determines the dissipation time scale, and is there submergence of magnetic flux when active regions decay?

In this article, we present some recent results on the dynamics of active regions obtained by time-distance helioseismology (Duvall *et al.*, 1993), addressing some of these questions.

2. New Methods of Investigating Solar Dynamics

Time-distance helioseismology measures travel times of acoustic waves propagating to different distances, and uses these measurements to infer variations of the wave speed along the wave paths. Turbulent convection excites acoustic waves which propagate deep into the solar interior. Because the sound speed increases with depth these waves are refracted and come back to the solar surface. The wave speed depends on temperature, magnetic field strength and flow velocity field in the region of the wave propagation. By measuring reciprocal travel times of acoustic waves propagating along the same ray paths in opposite directions, and then taking the mean and the difference of these travel times it is possible to separate the flow velocity (advection) effect from temperature and magnetic field perturbations (Kosovichev and Duvall, 1997). However, in order to disentangle contributions of temperature and magnetic field to the mean travel times it is necessary to measure the travel-time anisotropy, and this has not been accomplished. Therefore, the current helioseismic results represent maps of sub-photospheric variations of the sound (magneto-acoustic) speed and flow velocities.

The travel times are typically measured from a cross-covariance function of solar oscillation signals for various distances and time lags. When for a given distance the time lag corresponds to the propagation time of acoustic waves for this distance, a wavepacket-like signal appears in the cross-covariance function. The

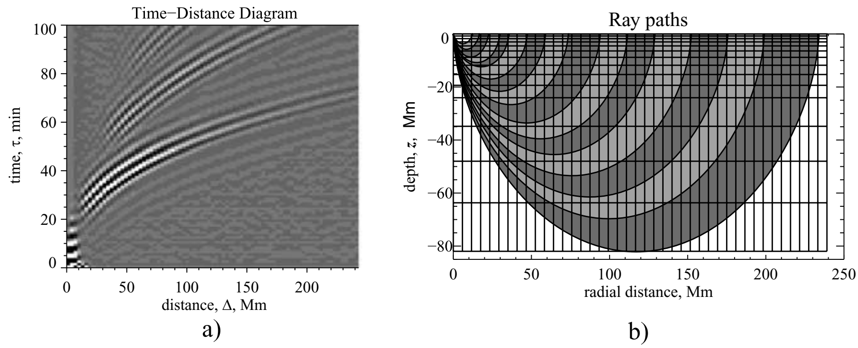

Figure 1. (a) Cross-covariance functions of solar oscillations as a function of distance between measurement points on the solar surface and time lag. The lowest ridge is formed by the acoustic wave packets propagating between these points through the solar interior. The solid curve shows the time-distance relation in the ray approximation. The higher ridges are formed by the wave packets with additional bounces at the surface. (b) a sample of acoustic ray paths used for time-distance helioseismology, shown in a vertical plane. The shadowed regions illustrate ranges of averaging. The vertical and horizontal lines show a grid used for inversion of acoustic travel time data.

cross-covariance plotted as a function of the distance and time lag displays a set of ridges formed by the wave-packet signals (Figure 1a), representing an analog of a solar ‘seismogram’. Since the solar oscillations are stochastic it is necessary to use the oscillation signals at least 4–8 hour long and also average them over some surface (typically, circular) areas in order to obtain a sufficient signal-to-noise ratio. Then, the travel times are determined by fitting a wavelet to this function (e.g. Kosovichev and Duvall, 1997), or by measuring displacement of the ridges (Gizon and Birch, 2002).

The relationship between the observed travel-time variations and the internal properties of the Sun is given by so-called sensitivity kernels through integral equations. These integral equations are solved by standard mathematical inversion techniques such as LSQR and Multi-Channel Deconvolution (MCD) (Couvidat *et al.*, 2004). The sensitivity functions are calculated using a ray theory (Figure 1b) or more complicated wave perturbation theories, e.g. Born approximation, which takes into account the finite wave-length effects (Birch and Kosovichev, 2000). These theories can also take into account stochastic properties of acoustic sources distributed over the solar surface (Gizon and Birch, 2002; Birch *et al.*, 2004).

3. Lifecycle of Active Regions

Helioseismic observations show that the flow dynamics changes during the evolution of active regions. One of the important tasks is to develop diagnostics of emerging active regions in the interior. For space weather predictions it would be

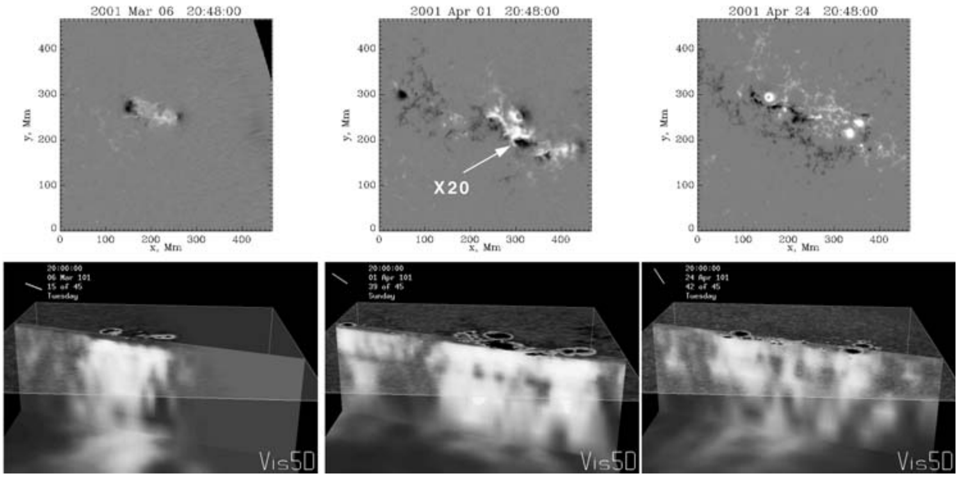

Figure 2. The sound-speed perturbation below the surface and photospheric magnetograms in the emerging active region NOAA 9393. The upper panels are MDI magnetograms showing the surface magnetic field of positive (light) and negative (dark) polarities. The perturbations of the sound speed shown in the vertical cut and the bottom horizontal panel, are approximately in the range from –1 to +1 km/s. The positive variations are shown in light color, and the negative ones in dark. The top (semitransparent) panels are white-light images, the bottom panels show the sound-speed maps 57 Mm deep. The arrow shows the location of the powerful X20 flare on April 2, 2001.

very important to detect active regions before they emerge. However, this task has proven to be very difficult because the emerging magnetic flux propagates very rapidly in the upper convection zone with a speed exceeding 1 km/s (Kosovichev *et al.*, 2000).

Here we present as an example the evolution of active region NOAA9393, which was observed in March to May 2001 during the Dynamics Program for the MDI instrument on SOHO. Almost uninterrupted series of full-disk Dopplergrams with the resolution 2 arc sec per pixel and 1-min cadence were obtained. For the time-distance analysis, travel distances from 0.3 to 24 degrees were used (Kosovichev and Duvall, 2003). The inversion results (Figures 2–6) produced 3D maps of the sound-speed variations and mass flows in a cube of $400 \times 400 \times 80$ Mm for 3 periods, when the active region was on the front side of the Sun, during Carrington rotations 1973, 1974 an 1975. The total number of interior maps included in this analysis is 45. The integration time for a single map was 8 hours. Therefore, typically three maps per day were obtained. The analyzed dates are: March 2–6, March 25–April 1, and April 24–25, 2001. These include the periods of emergence, maximum activity and decay of this active region. The initial results show complicated patterns of rapidly evolving sound-speed perturbations most likely associated with multiple interacting magnetic flux tubes.

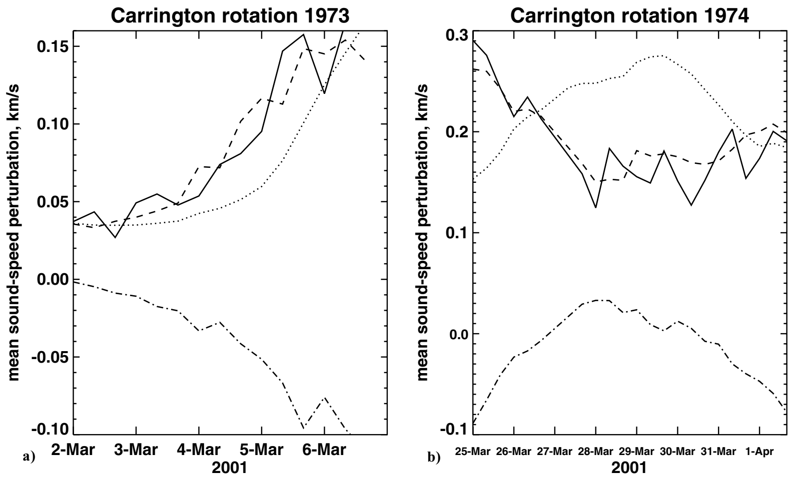

Figure 3. The evolution of the total unsigned magnetic flux (dotted curves) and the mean sound-speed perturbation at 0–3 Mm (dot-dashed curves), 4–12 Mm (dashed curves) and 15–34 Mm (solid curves), during Carrington rotations 1973 and 1974, periods of emergence and maximum development of the active region, NOAA 9393.

The evolution of the total photospheric magnetic flux and mean sound-speed perturbations at various depths in this active region is shown in Figure 3. It appears that during the emergence and development phase (Figure 3a) the sound-speed perturbations in the deeper layers, 4–34 Mm, grow somewhat faster than the magnetic flux, and in the subsurface layer (0–3 Mm) the sound-speed rapidly decreases. During the maximum phase (Figure 3b) the sound-speed behavior is opposite. It decreases in the deep interior in antiphase with the magnetic flux, and in the near-surface it changes almost in phase with the magnetic flux which, however, lags the sound-speed variations.

Time-distance helioseismology also provided maps of plasma flows beneath this active region. Figure 4 shows the distribution of the photospheric magnetic field and horizontal and vertical flow maps in the subsurface layers 2 and 6.4 Mms deep, shown in Figure 4b and c. Beside the usual supergranular flows these maps do not reveal any specific flow pattern that could be associated with emergence of a large-scale structure, e.g. a large-scale outflow or upflow. However, a localized shearing flow appears at the place of emergence. Soon after the emergence, the dominant flow pattern consists of converging downflows around the active regions (Kosovichev, 1996; Zhao *et al.*, 2001). Figure 5 shows the active region dynamics during the maximum activity phase. The flow structure is quite complicated. In addition to the converging downflows surrounded by upflows we see a diverging flow around a rapidly evolving leading spot. Also, there is evidence for strong shear flows in the central part of this region where a very strong flare occurred 3 days later, on April 2. The decaying phase shown in Figure 6 is characterized by predominant outflows.

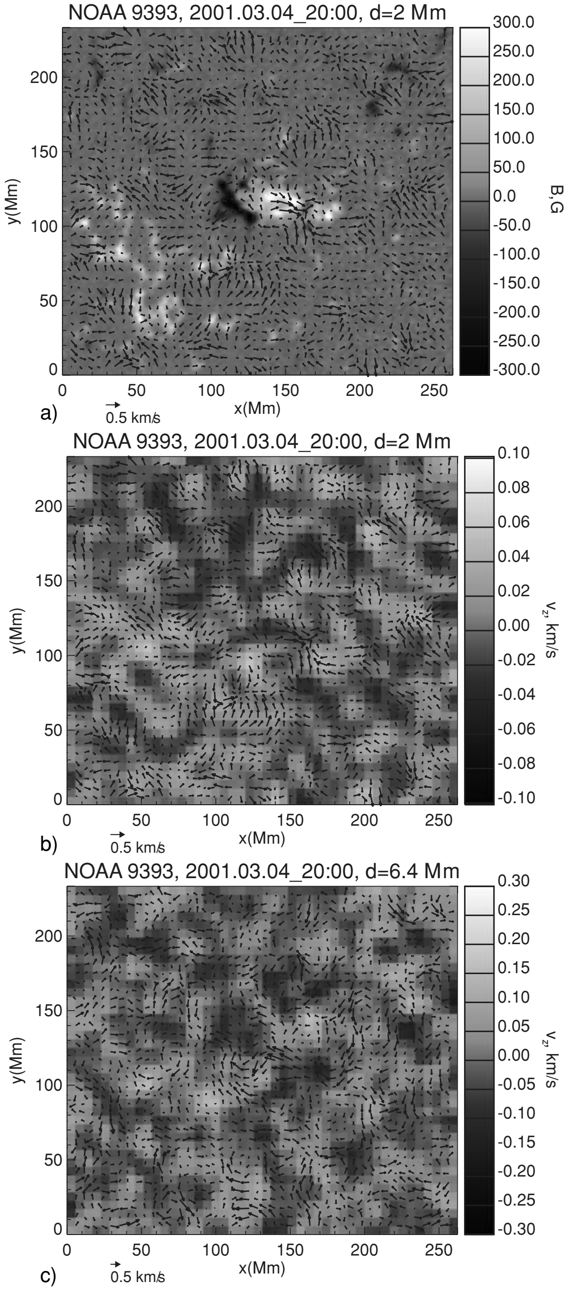

Figure 4. Emergence of active region NOAA 9393 (March 4, 2001): (a) the photospheric magnetic field and the horizontal velocity field at a depth of 2 Mm; (b) the vertical (the grayscale map; positive – upflows, negative – downflows) and horizontal velocity fields at the depth of 2 Mm; (c) the vertical and horizontal velocities at the depth of 6.4 Mm.

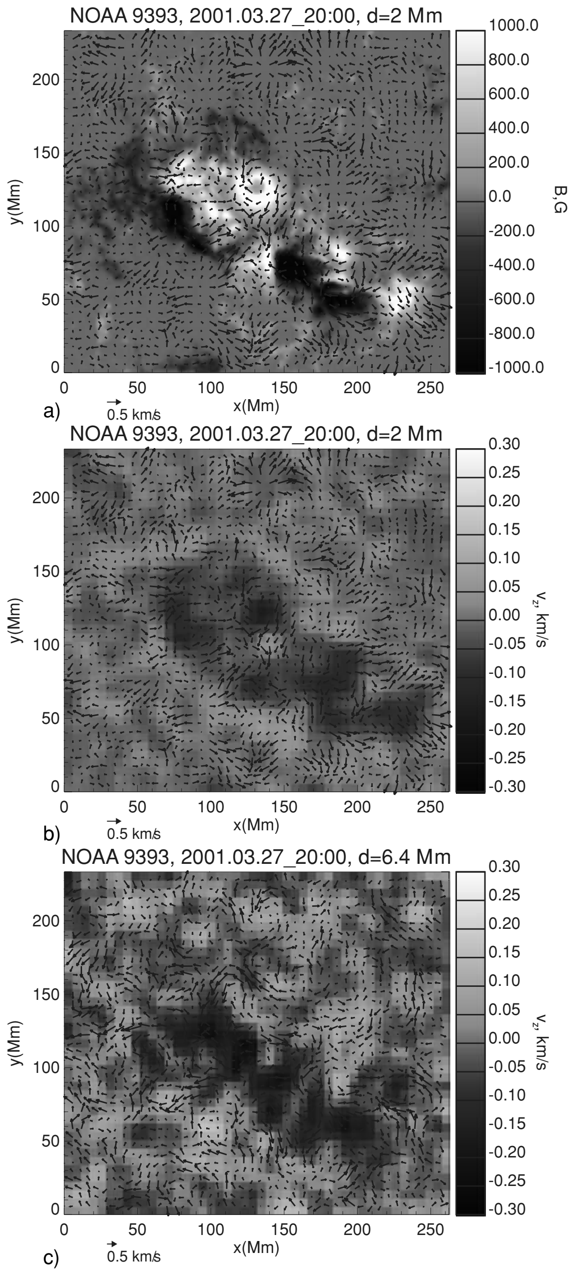

Figure 5. The maximum activity phase of AR 9393 (March 27, 2001): (a) the photospheric magnetic field and the horizontal velocity field at a depth of 2 Mm; (b) the vertical (the grayscale map; positive – upflows, negative – downflows) and horizontal velocity fields at the depth of 2 Mm; (c) the vertical and horizontal velocities at the depth of 6.4 Mm.

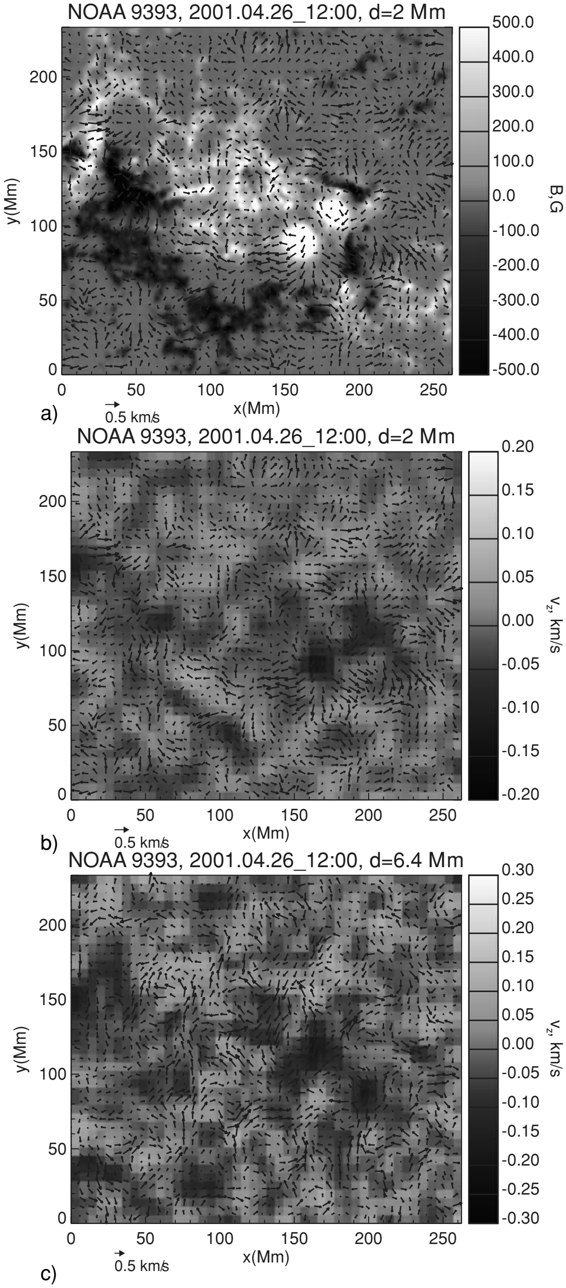

Figure 6. The decay phase of AR 9393 (April 26, 2001): (a) the photospheric magnetic field and the horizontal velocity field at a depth of 2 Mm; (b) the vertical (the grayscale map; positive – upflows, negative – downflows) and horizontal velocity fields at the depth of 2 Mm; (c) the vertical and horizontal velocities at the depth of 6.4 Mm.

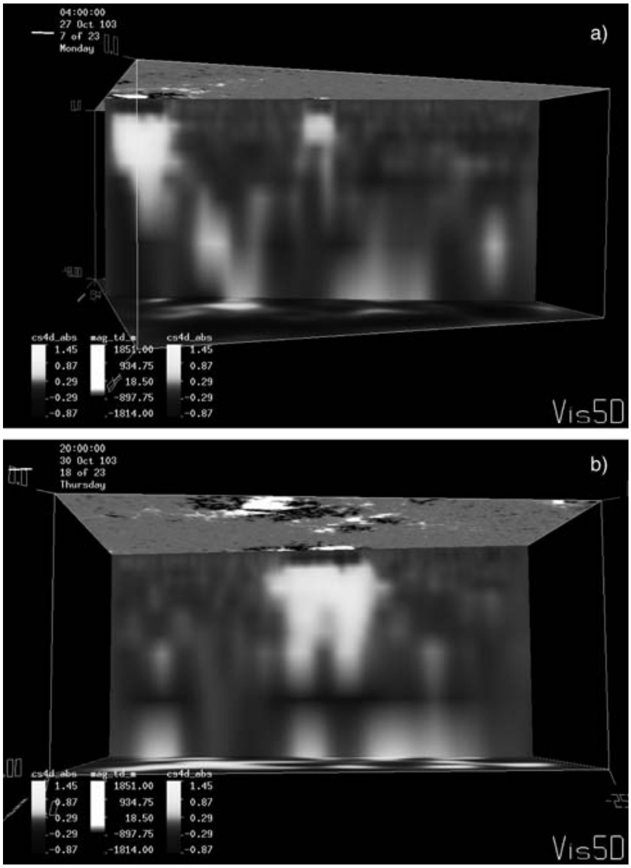

Figure 7. Sound-speed variations (vertical cuts) associated with developing active region NOAA 10488 (October 2003): (a) emergence of the active region in the middle of the domain (the structure near the right boundary is AR10486; (b) fully developed AR 10488. The depth of the box is 48 Mm, the horizontal size is about 540 Mm. The sound-speed scale is from –1 to 1.5 km/s, the scale of the photospheric magnetic field shown in the upper panel (view from below the surface) is from –1800 to 1800 Gauss.

The sound-speed and flow maps reconstructed up to a depth of 60 Mm reveal that the subsurface structure of the active region is as complicated as its surface structure, and also rapidly evolving. From these observations, we find no evidence for a large magnetic Ω-loop emerging from the interior and forming this active region. The active region was rather formed by fragmented magnetic flux emerging during an extended period of time. However, the sound-speed image of another large active region NOAA 10488 reveals a large-scale loop-like structure below the surface (Figure 7). Obviously, more observations are needed for understanding the structure and evolution of active regions.

4. Dynamics of Active Regions and Sources of Heliospheric Disturbances

During the maximum of activity the helioseismic observations show large-scale converging downflows accompanied by complicated shearing motions which may be related to flaring activity (Dzifcakova *et al.*, 2003; Kulinova *et al.*, 2003). During the decay phase the downflows become significantly weaker, and diverging flows around decaying sunspots are observed.

A series of 9 X-class flares produced during Oct. 23–Nov. 4, 2003, by the two active region 10486 and 10488 was one of the most powerful in the history of solar observations. It is well-known that flares usually occur in complex sheared and twisted magnetic configurations which are presumably produced by shearing and twisting plasma flows below the surface where the dynamic pressure of plasma flows may exceed the magnetic pressure. Magnetic energy release in solar flares typically happens around neutral lines of the line-of-sight (vertical) component of magnetic field. These places can be identified by rapid permanent changes of the photospheric magnetic flux on both sides of the neutral line. The true height

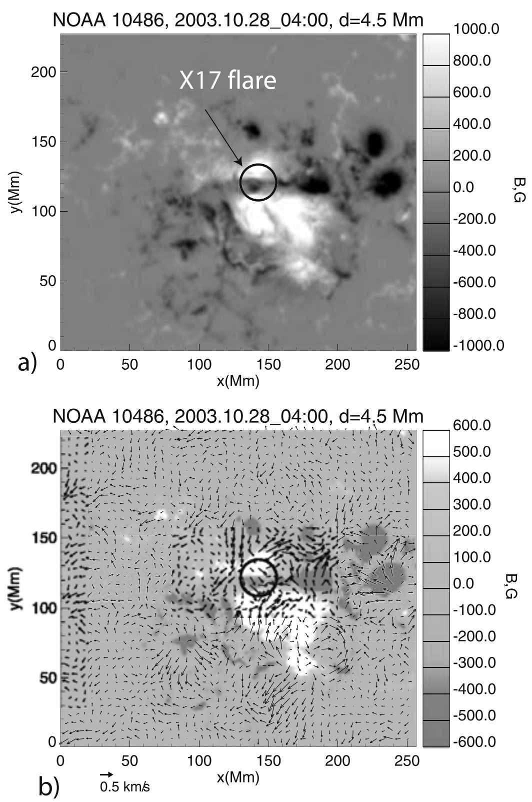

Figure 8. Surface magnetograms and subsurface flows during the X17 flare of October 28, 2003.

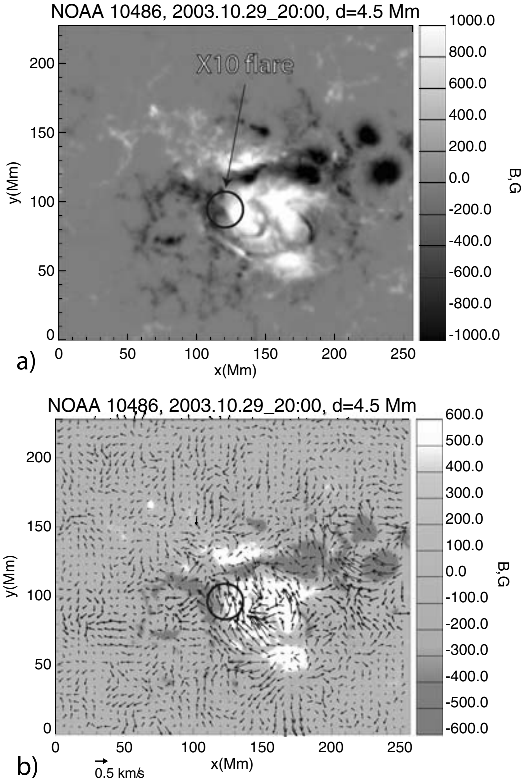

Figure 9. Surface magnetograms and subsurface flows during the X10 flare of October 29, 2003.

of the magnetic energy release is still not established. Presumably the energy is released mostly in magnetic structures in the upper atmosphere, covering some range of heights, but evidently these structures are connected to the places in the photosphere where we see significant permanent magnetic flux changes during the impulsive phase of solar flares.

The black circles in Figures 8 and 9 indicate the sites of the magnetic energy release for two strong flares, X17 started at 9:51 UT on October 28, and X10 started at 20:37 UT on October 29. It is intriguing that the flow maps inferred by time-distance helioseismology at the depth of 4–6 Mm reveal strong (with speed about 1–2 km) shearing flows directed to the sites of the magnetic energy release during these flares. This is particularly evident from the flow map (Figure 8b, taken for the 8-hour periods: 0–8 UT on October 28 (labeled as 2003.10.28_04: 00, just before the X17 flare), and from the flow map (Figure 8b, obtained for 16–24 UT on October 29 (2003.10.29_20: 00), before and during the X10 flare.

Obviously, the 8-hour resolution of our time-distance measurement does not allow us to follow the plasma dynamics during the flares which happen on a much shorter time scale. Nevertheless, these results indicate that some interesting dynamics associated with flaring activity probably occurs in subsurface regions, 4–6 Mm deep, just below the zone where the strong magnetic field of sunspots inhibits convection (Zhao *et al.*, 2001).

In conclusion, the new methods of local helioseismology provide powerful diagnostics of sub-photospheric dynamics of active regions, which allow us to investigate the birth and evolution of active regions, and origins of solar activity. Further analysis should include more accurate flow maps with high temporal and spatial resolutions, and determine links between the interior dynamics and coronal magnetic fields of active regions.

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SUNSPOT STRUCTURE AND DYNAMICS

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Abstract. Sunspots are the most prominent magnetic features on the Sun but it is only within the last few years that the intricate structure of their magnetic fields has been resolved. In the penumbra the fields in bright and dark filaments differ in inclination by 30°. The field in the bright filaments is less inclined to the vertical, while the field in dark filaments becomes almost horizontal at the edge of the spot. Recent models suggest that this interlocking-comb structure is maintained through downward pumping of magnetic flux by small-scale granular convection, and that filamentation originates as a convective instability. Within the bright filaments convection patterns travel radially owing to the inclination of the field. A proper understanding of these processes requires new observations, from space and from the ground, coupled with large-scale numerical modelling.

Keywords: sunspots – Sun: magnetic fields

1. Introduction

Sunspots have been observed through telescopes for almost 400 years and early observers, such as Galileo, Scheiner and Hevelius, were already able to distinguish the dark central core of a spot (the *umbra*) from the fuzzier annulus (the *penumbra*) that surrounds it. The filamentary structure of the penumbra was not recognized till two centuries later, when achromatic lenses were available, and it was only in 1908 that Hale used the Zeeman effect to show that sunspots were the sites of kilogauss magnetic fields. Forty years later, magnetohydrodynamics had been established and it was realised that sunspots were dark because normal convective transport was inhibited by their strong magnetic fields. However, it is only within the last ten years that it has become possible to observe the fine structure of the penumbral magnetic field, with telescopes that are capable of arc-second or sub-arc-second resolution – and these measurements have posed questions that theorists are still struggling to answer. So the structure of sunspots may be an old problem but it raises issues that are very much alive today.

There are several recent reviews of this subject, by Solanki (2003), by Thomas and Weiss (2004) and by Tobias and Weiss (2004), in order of decreasing detail. In this brief survey I shall first summarize the observational results and outline the physical picture that arises from them. Next, in Section 3, I shall discuss the crucial mechanism of flux pumping, which appears to be responsible for maintaining the

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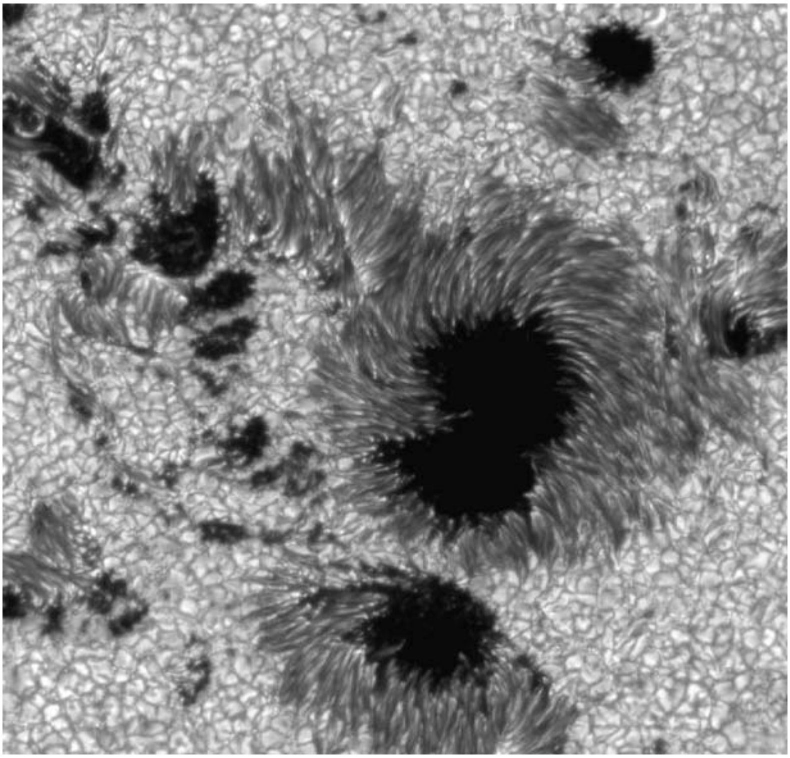

Figure 1. Sunspots observed with the 1-m Swedish Solar Telescope on La Palma, at 0.1 arc-sec resolution. The dark umbra of the central spot is surrounded by a filamentary penumbra with a total diameter of about 25 Mm. There are several dark pores (e.g. at top right) without penumbrae as well as smaller micropores. The background pattern of convection cells, with diameters of order 1 Mm, is the solar granulation. This image, obtained in the CH G-band, also shows tiny bright features, which correspond to small magnetic flux elements nestling between the granules. (Courtesy of the Royal Swedish Academy of Sciences.)

penumbra's filamentary structure. Then, in the final section, I shall comment on some outstanding problems and point to future progress.

2. The Magnetic Structure of a Sunspot

The remarkable high-resolution image in Figure 1 shows two sunspots with filamentary penumbrae, as well as several pores (without penumbrae) and various smaller magnetic features (Scharmer *et al.*, 2002; Rouppe van der Voort *et al.*, 2004). The strong magnetic fields in the spots suppresses the normal pattern of small-scale convection – the solar granulation – in the photosphere surrounding them, where bright hot plumes are enclosed by a network of cooler sinking gas.

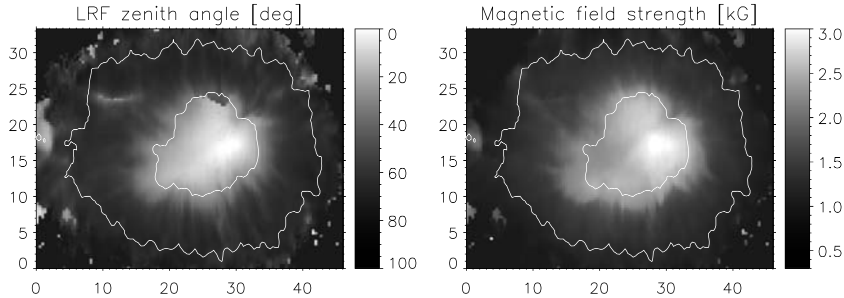

Figure 2. Fine structure of the penumbral magnetic field. Right panel: Field strength. Left panel: inclination of the field to the local vertical. The average inclination increases towards the edge of the spot but azimuthal variations in inclination are clearly visible. (After Bellot Rubio, 2003.)

The azimuthally averaged magnetic field is vertical at the centre of an isolated sunspot and its inclination to the vertical increases with increasing radius, reaching a value of 70° at the edge of the penumbra, as shown in Figure 2. It has long been known, however, that there is a persistent horizontal outflow (the Evershed flow) in the outer part of the penumbra. Since the velocity should be parallel to the field in such a highly conducting plasma, this raises an apparent contradiction (Adam and Petford, 1990), which can only be resolved by assuming an inhomogeneous magnetic structure (Beckers and Schröter, 1969).

High-resolution observations (e.g. Title *et al.*, 1993; Lites *et al.*, 1993; Solanki and Montavon, 1993; Stanchfield *et al.*, 1997; Bellot Rubio, 2003; Bellot Rubio *et al.*, 2003; Borrero *et al.*, 2004; Bellot Rubio, *et al.*, 2004; Bello González *et al.*, 2005) have subsequently confirmed that the inclinations of the fields in bright and dark filaments do indeed differ by 30–40°, as can be seen in Figure 2. The fields in the dark filaments (which carry the Evershed flow) are more inclined to the vertical, becoming almost horizontal at the outer edge of the spot. The most recent measurements, obtained at exceptionally high resolution with the Swedish Solar Telescope on La Palma (Langhans *et al.*, 2005), clearly distinguish between a darker component, with a weaker field that is more inclined, and a brighter component with a stronger field that is more nearly vertical (though the anticorrelation between field strength and inclination is more marked than that between brightness and inclination). Thus the penumbral magnetic field has the improbable interlocking-comb structure that is shown schematically in Figure 3. Moreover, the two families of field lines are apparently distinct, for the loops that follow field lines emerging from bright filaments extend across vast distances, as is apparent from the TRACE image in Figure 4, while the fields associated with dark filaments either hug the surface (forming a superpenumbra in Hα) or actually plunge beneath it.

The observed Evershed flow is confined to thin channels, which are indeed aligned with the most nearly horizontal fields (Bellot Rubio *et al.*, 2003, 2004; Tritschler *et al.*, 2004; Schlichenmaier *et al.*, 2004), though the correlation with

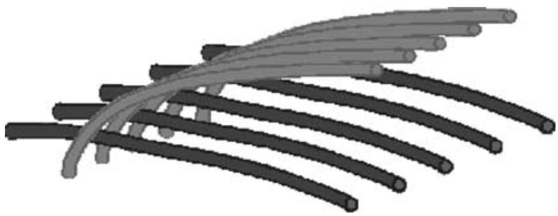

Figure 3. Sketch showing the interlocking-comb structure of the magnetic field (represented schematically by flux tubes) in the penumbra of a sunspot, with inclined fields in the bright filaments and almost horizontal fields in the dark filaments. (Courtesy of N. H. Brummell.)

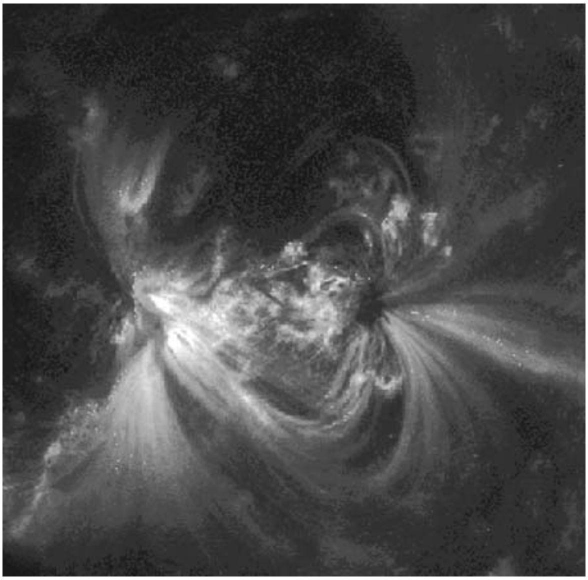

Figure 4. TRACE image of a sunspot pair, showing coronal loops that follow magnetic field lines emerging the penumbrae of the spots and extending far across the surface of the Sun. (Courtesy of the Lockheed-Martin Solar and Astrophysics Laboratory.)

dark filaments is somewhat weaker (Rimmele, 1995a; Stanchfield *et al.*, 1997; Schlichenmaier *et al.*, 2005). Furthermore, many of the flow channels that emerge in the penumbra actually turn over and dive down either just outside it or even within it, carrying both the flow and its associated magnetic field with them (e.g. Rimmele, 1995b; Stanchfield *et al.*, 1997; Westendorp Plaza *et al.*, 1997; del Toro Iniesta *et al.*, 2001; Bellot Rubio *et al.*, 2003, 2004; Tritschler et al., 2004; Schlichenmaier *et al.*, 2005; Borrero *et al.*, 2005; Langhans *et al.*, 2005). It is generally supposed that the Evershed flow is in fact a siphon flow along these flux tubes, driven by pressure differences between their footpoints (Meyer and Schmidt, 1968; Montesinos and Thomas, 1997).

3. Flux Pumping by Convection

These observations raise serious theoretical problems. First of all, we need to explain the interlocking-comb magnetic structure illustrated in Figure 3, which is really a structure of interlocking sheets, for continuity of magnetic flux requires that the two families of field lines must have a finite vertical extent. (This structure is often referred to as ‘uncombed’, following Solanki and Montavon, 1993.) In addition, the unexpected reversal of the vertical component of the magnetic field in the outer penumbra demands an explanation. In fact, it is this reversal that offers a key to understanding how this strange coherent structure can be maintained.

There are two effects that resist downward bending of magnetic flux tubes: the magnetic curvature force tends to straighten field lines, while magnetic buoyancy makes an isolated flux tube rise. Hence there has to be some other effect that drags them down below the surface, either inside the penumbra itself or just outside it. The obvious candidate is downward pumping of magnetic flux by the small-scale, turbulent granular convection within the large annular ‘moat’ cell that surrounds a well-developed spot. This process leads to the overall picture of a sunspot that is shown schematically in Figure 5 (Thomas *et al.*, 2002; Weiss *et al.*, 2004). (Note that the magnetic field actually fills the space above the sunspot and has an interlocking-sheet structure in the penumbra; it is nevertheless convenient to represent this field

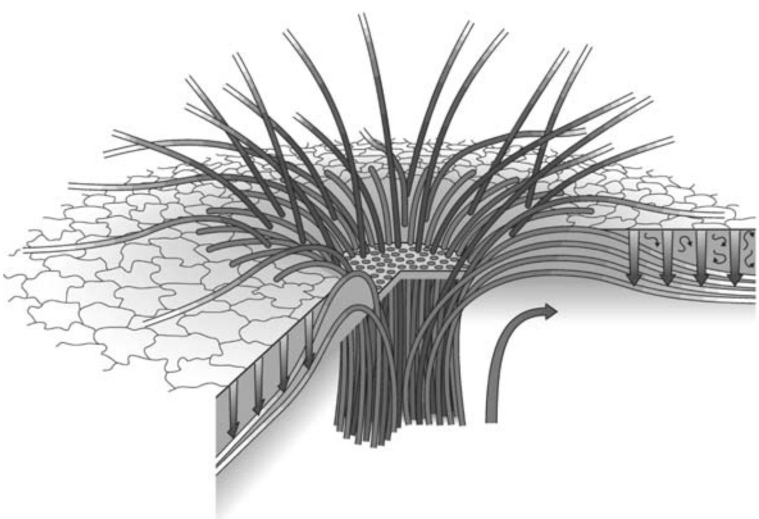

Figure 5. Schematic representation of a sunspot, showing isolated flux tubes emerging from the umbra and penumbra. Flux tubes that emerge from the penumbra either form a canopy over the photosphere or are pumped downwards by granular convection outside the sunspot and held below the surface. There is also a large-scale radial outflow in the annular moat cell that surrounds the sunspot. (From Weiss et al., 2004.)

by depicting isolated flux tubes.) In this picture it is supposed that the Evershed flow is carried by flux tubes that arch above the penumbral photosphere before returning below it, and are then kept submerged by the downdrafts at the boundaries of granules, This picture is supported by the behaviour of moving magnetic features in the moat, which correspond to a stitch of field emerging as a bipolar feature and travelling radially outwards (see Thomas and Weiss, 2004 for further details).

Flux pumping has been studied numerically in some highly idealized configurations, first in relation to the solar tachocline (e.g. Tobias et al., 2002; Dorch and Nordlund, 2002), and then in the present context. Two processes are involved: one is the expulsion of magnetic flux down the gradient of turbulent intensity (e.g. Tao *et al.*, 1998) and the other is the tendency of convection in a stratified layer to pump magnetic flux preferentially downwards. Numerical simulations show a distinction between broad, gently rising plumes that expand as they move upwards and narrow, vigorously sinking plumes that entrain material as they descend. As a result, an initially horizontal field is pumped downwards out of a vigorously convecting region and can accumulate in an adiabatically (or mildly superadiabatically) stratified layer beneath it (Weiss *et al.*, 2004). Figure 6 shows some results with a somewhat more realistic configuration (Brummell et al., 2006). The strongly unstable region has an aspect ratio of $6 \times 6 \times 1$ but the full computational box extends further downwards, with aspect ratio $6 \times 6 \times 3$, and the lower part is mildly subadiabatically stratified. Once convection is fully established, a strong magnetic field is added, with the double-arched structure shown in the upper panel (and periodic lateral boundary conditions). After the calculation has reached a statistically steady state, the horizontal fields are pumped downwards, excluded from the vigorously convecting region, and stored in the stably stratified layer below. More elaborate calculations are clearly needed but it appears already that this process is robust and able to explain the observed behaviour of the fields that carry the Evershed flow in sunspots.

4. Outstanding Problems

High-resolution observations have finally revealed the intricate structure of the magnetic field in the penumbra of a sunspot, and there is a plausible theoretical picture of how this structure is maintained. There is, however, a range of associated problems where theory is in a weaker state.

It is natural to ask how the interlocking-comb structure originates as a sunspot is formed. Sunspots are formed by the amalgamation of smaller pores, which resemble isolated umbrae. (On close inspection, the small pores in Figure 1 do themselves have a very fine-scale fluted structure at their edges.) Model calculations have confirmed that the average inclination of the field at the edge of a pore increases as the magnetic flux in the pore itself increases, and it has been conjectured that a subcritical fluting instability sets in when the inclination reaches a critical value (Rucklidge *et al.*, 1995). Simplified model calculations in Cartesian geometry have

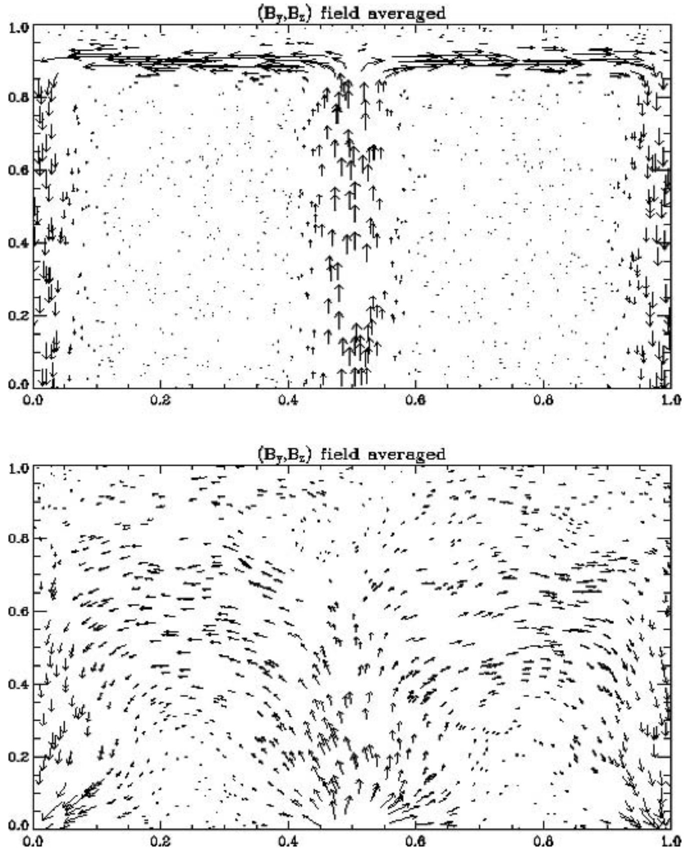

Figure 6. An idealised model of flux pumping in a sunspot. The upper panel shows the initial magnetic field, which lies in the yz-plane, referred to Cartesian co-ordinates with the z-axis vertical. The computation is three-dimensional and fully compressible; the upper third of the box is strongly unstable, while the lower part is weakly subadiabatic. The lower panel shows the magnetic configuration after some time has elapsed, with the field averaged in the transverse x-direction. The arched structure has been depressed and weakened, and the ordered field is pumpeddownwards out of the vigorously convecting region. (Courtesy of N. H. Brummell.)

demonstrated that there is a three-dimensional, convectively driven instability that leads to a fluted structure at the outer boundary of an isolated flux concentration, and that this saturates at a moderate amplitude (Tildesley, 2003; Tildesley and Weiss, 2004). Hurlburt and Alexander (2003) have also studied the development of a non-axisymmetric $m = 12$ fluting mode in cylindrical geometry as the total magnetic flux is increased. as shown in Figure 7. These results indicate that in the solar context there must be a non-axisymmetric, convectively driven instability that leads to a fluted structure at the outer boundary of a protospot and the formation of a rudimentary penumbra. Flux tubes that are depressed can then be grabbed by convective downdrafts and pumped downwards to form a regular penumbra

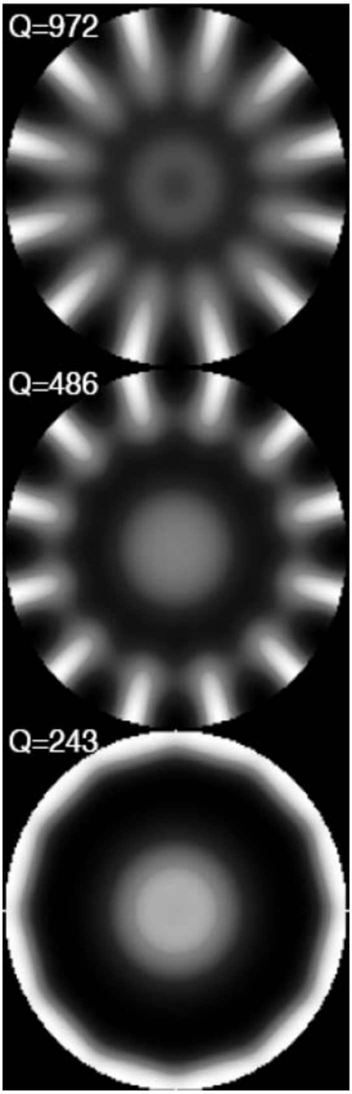

Figure 7. Development of a fluted magnetic structure for nonlinear compressible magnetoconvection in cylindrical geometry. The imposed magnetic flux Φ through the cylindrical domain is measured by the Chandrasekhar number $Q \propto \Phi^2$ and the shading represents the magnetic field at the upper boundary. When the field is weak this numerical experiment yields an axisymmetric pattern but as Q is increased a non-axisymmetric instability appears and grows. Since the calculation is actually restricted to a 30° wedge, only an $m = 12$ mode is present. (After Hurlburt and Alexander, 2003.)

(Tildesley and Weiss, 2004). When a spot decays, this configuration can be retained as the total flux decreases below the critical value – and observations do indeed show that the largest pores are bigger than the smallest spots.

It has long been realised that energy transport in pores or sunspots relies on convection rather than on radiation. Indeed, sunspots have provided the principal motivation for studying magnetoconvection (Proctor, 2004). There is obviously a great difference between umbral and penumbral patterns of convection (Hurlburt *et al.*, 2000; Weiss, 2002). In the umbra, where the field is nearly vertical, convection apparently takes the form of slender, spatially modulated oscillations, which give rise to small, bright umbral dots. Penumbral convection must take different forms in bright and dark filaments. In the bright filaments, with inclined magnetic fields, patterns are expected to travel as waves – and there are indeed bright features ("grains") that migrate inwards or outwards, depending on the inclination of the field. In the dark filaments, with almost horizontal fields, some form of interchange is more likely. However, there is as yet no detailed understanding of any of these convective processes.

Sunspots have been known for centuries but their global structure could not be explained until high resolution images were obtained, within the last few years. In the future we can expect yet finer scale features to be resolved, along with Doppler and Zeeman measurements of associated velocities and magnetic fields, not only from the 1-m Swedish Solar Telescope and the Dunn Telescope at Sacramento Peak (with the advantage of adaptive optics) but also from Solar-B and the Solar Dynamics Observatory in space and, in due course, from the Advanced Technology Solar Telescope. It is clear from all the preceding discussion that observations still lead theory in this subject. Theoretical modelling has produced a general picture but further progress must rely on much more detailed models, coupled with a deeper physical and mathematical understanding of the nonlinear processes that are involved. Fortunately, we can rely on the continuing rapid development of high performance computing, on massively parallel machines and clusters, which makes it possible to develop much more sophisticated and elaborate numerical models. This combination of theory with new observations makes it an exciting time to be working on this old subject!

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