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Doubts about the crucial role of the rising-tube mechanism in the formation of sunspot groups

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Abstract

Some preliminary processing results are presented for a dataset obtained with the Solar Optical Telescope on the *Hinode* satellite. The idea of the project is to record, nearly simultaneously, the full velocity and magnetic-field vectors in growing active regions and sunspot groups at a photospheric level. Our ultimate aim is to elaborate observational criteria to distinguish between the manifestations of two mechanisms of sunspot-group formation — the rising of an Ω-shaped flux tube of a strong magnetic field and the in situ amplification and structuring of magnetic field by convection (the convective mechanism is briefly described).

Observations of a young bipolar subregion developing within AR 11313 were carried out on 9–10 October 2011. During each 2-h observational session, 5576-Å filtergrams and Dopplergrams were obtained at a time cadence of 2 min, and one or two 32-min-long spectropolarimetric fast-mode scans were done. Based on the series of filtergrams, the trajectories of corks are computed, using a technique similar to but more reliable than local correlation tracking (LCT), and compared with the magnetic maps. At this stage of the investigation, only the vertical magnetic field and the horizontal flows are used for a qualitative analysis.

According to our preliminary findings, the velocity pattern in the growing active region has nothing to do with a spreading flow on the scale of the entire bipolar region, which could be expected if a tube of strong magnetic field emerged. No violent spreading flows on the scale of the entire growing magnetic region can be identified. Instead, normal mesogranular and supergranular flows are preserved. Signs of small-scale structuring of the magnetic field can be detected in the area where new spots develop, and signs of the presence of separatrices between the magnetic polarities can be found, such that the surface flows converge to but not diverge from these separatrix curves. The observed scenario of evolution seems to agree with Bumba's inference that the development of an active region does not entail the destruction of the existing convective-velocity field. The convective mechanism appears to be better compatible with observations than the rising-tube mechanism.

In the umbras of the well-developed sunspots, flows converging to the umbra centres are revealed. Spreading streams are present around these spots.

Keywords: Solar photosphere; Solar convection; Magnetic fields; Sunspot formation; Hinode observations

1. Introduction

The idea that the magnetic field of a bipolar sunspot group originates from the emergence of an Ω-shaped flux-tube loop was considered to be virtually indisputable for a long time. According to this *rising-tube model*, the flux

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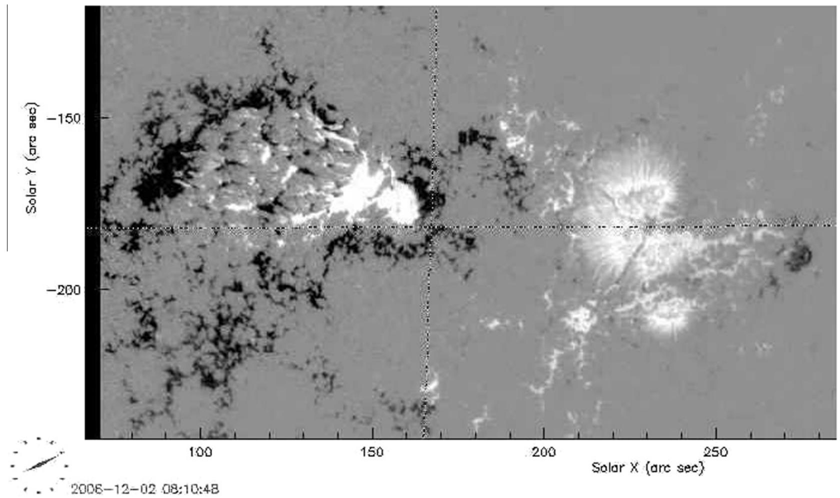

Fig. 1. Fragment of a line-of-sight (Stokes V) magnetogram of AR 10926, where a sunspot group is developing. The magnetogram was obtained on 2 December 2006 at 08:10:48 UT with the Solar Optical Telescope on the *Hinode* satellite. Black represents negative polarity, and white represents positive.

tube forms in the general solar toroidal magnetic field deep in the convection zone, and the field that it carries upward is already strong before the rise. This mechanism received much attention after a well-known study by Parker (1955a), who invoked magnetic buoyancy to account for the rise of flux-tube loops, and has been revisited by a number of investigators over several decades. Interesting analyses of this model were made, in particular, by Caligari et al. (1995) and Caligari et al. (1998); numerical simulations of this mechanism based on full systems of MHD equations have also been carried out (see, e.g., Fan et al. (2013), Rempel and Cheung (2014), and references therein).

In recent years, however, the rising-tube model has more and more been objected based on both recent, very detailed observational data and current views of the processes in deep layers. First, if it is adopted, one has to account for the origin of the coherent tube of strong magnetic field; to this end, some additional, fairly artificial assumptions need to be introduced. Second, which is very important, the pattern of photospheric flows and magnetic fields on the scale of the growing magnetic region predicted by this model disagrees with the pattern actually observed on the Sun (see, e.g., Kosovichev (2009) and our brief description of a remarkable magnetogram given below in this Introduction); we shall see that the results of the present study also scarcely conform to the scenario that should be expected if a large tube of strong field emerges. Kosovichev and Stenflo (2008) and Kosovichev (2009) also noted that the behaviour of the tilt angle of the bipolar magnetic regions is not consistent with the predictions based on the rising-tube model.

We postpone summarising the weak points of the rising-tube model to the conclusive section of our paper and give now only an impressive example of observed features that do not support this model. It can be found in a series of line-of-sight (Stokes V) magnetograms of AR 10926 taken on 2 December 2006 (see a fragment of an image of this series in Fig. 1). They were obtained on the *Hinode* satellite using the Solar Optical Telescope (SOT) in nearly the same way as the magnetograms considered here (see Kosugi et al. (2007), Tsuneta et al. (2008), and our Section 3).[1] As M. DeRosa noted in the discussion at a "Living with a Star" workshop in September 2007 (see NASA (2007)), "the emergence of the sunspot magnetism progressed in a very complex manner, with small pieces appearing to self-assemble into larger, more coherent structures." Specifically, the data for AR 10926 show a sunspot-formation process differing from what occurs if "a 'rope' of strong magnetic field beaches the visible surface of the Sun".

Indeed, our inspection of the movie of AR 10926 magnetograms reveals spreading flows related to the emerging magnetic field; however, they are finely structured and form cells resembling convection cells rather than a unique flow system on the scale of the entire magnetic region (see the upper left quadrant of Fig. 1). Furthermore, spreading flows are associated locally with each developing magnetic island rather than "globally" with the entire complex magnetic configuration (which could be expected if a tube emerged). In its appearance, such spreading is similar to the flow around an effervescent tablet on the water surface. An example of such a "tablet" is the magnetic feature in the right-hand side of the magnetogram.

Thus, the rising-tube mechanism no longer appears to determine a paradigm in the investigation of the development of local magnetic fields. On the other hand, alternative mechanisms have been suggested in the literature.

Before mentioning some of them, let us introduce some necessary terminological conventions. While the rising-tube mechanism assumes the original presence of an intense flux tube of the global toroidal magnetic field in deep layers, other known mechanisms do not require any strong initial field and ensure in situ magnetic-field amplification

[1] This series of magnetograms, including that reproduced in Fig. 1, can be found via <http://sdc.uio.no/search/>. A high-quality movie composed of the magnetograms of this series is available via a link at NASA (2007).

and structuring. We restrict ourselves only to processes on scales no larger than the size of an active region; here, they will be referred to as *local mechanisms*. On the other hand, local processes on scales comparable to or below the granular size, which do not play any decisive role in the formation of active regions, will also fall beyond our scope of attention. Local MHD mechanisms with inductive self-excitation of magnetic fields strongly coupled with fluid motions are of particular interest, since there is a variety of possibilities for their manifestation under solar conditions. They are usually termed *local dynamo mechanisms*. If the local dynamo action is due to thermal convection, we shall assign such a dynamo to *local convective dynamos*; they will be discussed in the next section.

Many investigations assume that local MHD processes contribute to the generation of the global solar magnetic field. Parker (1955b, 1957) describes a global dynamo in which the general poloidal field is regenerated from the toroidal field by cyclonically twisted Ω-shaped flux-tube loops. Elsasser (1956) also considers such swirled loops (without introducing the concept of magnetic buoyancy) to be an ingredient of the global dynamo mechanism. Parker (1970a,b) treats global dynamos in a more general astrophysical and geophysical context and derives equations describing the generation of large-scale fields. These (and some other) studies assume the local plumes to be "building blocks" of the global dynamo, for which the averaged effect of numerous plumes is important. There are also numerous studies of small-scale turbulent dynamos, which also do not specialise the resultant local magnetic structures — we mean, in particular, Vainshtein (1982), Wood and Moffatt (1985), Brandenburg et al. (1991), Charbonneau and MacGregor (1996) and many others.

We regard here local motions as a mechanism of local amplification and structuring of the magnetic field. The idea of local MHD dynamo traces back to Gurevich and Lebedinsky (1946), who related the amplification process to the effects of plasma motions; however, they did not attribute these motions to convection and even did not specify any particular type of motion.

Kitchatinov and Mazur (2000) investigated a hydromagnetic instability that can act on scales large compared to the granular size, producing a magnetic-flux concentration similar to those observed in sunspots. The process crucially depends on the presence of fluid motion and on the quenching of eddy diffusivity by the enhanced magnetic field with the plasma cooling down. This is a local mechanism, which, however, is not a dynamo in the strict meaning of this term.

Another local mechanism, which also does not qualify as a dynamo, is related to the so-called negative-effective-magnetic-pressure instability (NEMPI), see Warnecke et al. (2013) and references therein. It results from the suppression of the total turbulent pressure (the sum of hydrodynamic and magnetic components) by the magnetic field.

2. Convective mechanism: basic idea and its implications

Tverskoi (1966) attributed the local dynamo effect to the action of cellular convection on the magnetic field. He considered a simple kinematic model describing the formation of a magnetic bipole by an axisymmetric toroidal eddy in a perfectly conducting fluid, regarding such an eddy as a schematic representation of a convection cell (more specifically, a supergranular cell was meant). The action of Tverskoi's mechanism is illustrated in Fig. 2. The fluid particles move in circular trajectories, concentric in any meridional section. Such a velocity field is specified in an orthogonal coordinate system r, φ, χ, where φ is azimuthal angle and r and χ are polar coordinates in the meridional plane $\varphi = \text{const}$. The fluid velocity is

$$V_r = V_\varphi = 0, \quad V_\chi = V_0(r)[1 + (r/a)\cos\chi]^{-1},$$

where a is the radius of the circle $r = 0$ and V_0 is an appropriately chosen function such that $V_0(r) = 0$ at any r exceeding a certain value $r_0 < a$. Obviously, the circles of a given radius $r = \text{const}$ form a toroidal surface. One such surface is shown in Fig. 2. The magnetic field lines, which are initially straight and horizontal, are wound by the fluid motion around the tori; one magnetic field line is shown in the figure. The solution of the induction equation obtained by Tverskoi contains a component monotonically growing with time. If $a - r_0 \ll a$, the magnetic field lines form two flux concentrations, with oppositely directed magnetic fields, in the central part of the eddy. They are marked in the figure with two heavy antiparallel vertical arrows below them. The azimuthal arrangement of these concentrations corresponds to the direction of the initial field. Tverskoi's prediction was later qualitatively confirmed by nonlinear numerical simulations of magnetoconvection in the form of a pattern of hexagonal, Bénard-type cells (Getling, 2001; Dobler and Getling, 2004). In these simulations, the conditions of periodicity in the horizontal directions exerted a substantial stabilising effect on convection. The calculated magnetic field was strongly amplified, and a bipolar structure similar to that found by Tverskoi formed

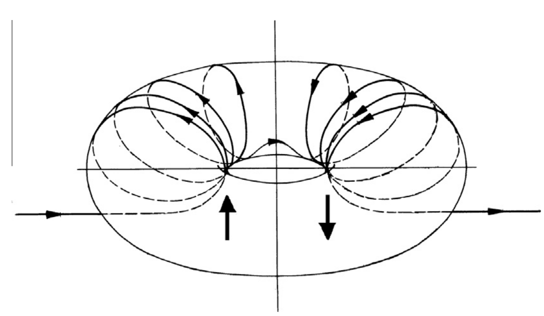

Fig. 2. Tverskoi's toroidal eddy winding a magnetic field line. One toroidal surface of the family forming the vortex is shown with a magnetic field line that has accomplished four revolutions with fluid particles moving over this surface. Two antiparallel heavy vertical arrows mark the flux concentrations of opposite polarities (slightly above).

in each convection cell. In addition, the vertical component of the magnetic field was enhanced in the contact zones between the hexagonal cells, i.e., in the intercellular lanes.

In essence, Tverskoi has demonstrated that the topology of the flow is very important in terms of the MHD effects of convection. He conjectured that supergranular convection cells, interacting with the azimuthal component of the global magnetic field[2] in nearly the same way as such eddies interact with the horizontal initial field, could produce the magnetic fields of bipolar sunspot groups. In this case, as can be seen from Fig. 2, the east–west orientation of the bipolar magnetic structures would result from the east–west direction of the global azimuthal field, with the same arrangement of polarities as in the case of the rise of a tube. The action of this mechanism would be controlled by the global azimuthal magnetic field, which provides initial conditions for each individual field-amplification event. Thus, Tverskoi's model appears to be as successful as the rising-tube model in terms of agreement with the global properties of solar activity such as the Hale polarity law.

Other local dynamos, which are based on granular and supergranular motions in the quiet photosphere, can account for fairly disordered magnetic fields on very small scales (Cattaneo, 1999; Vögler and Schüssler, 2007). In essence, only Stein and Nordlund (2012) used "realistic" numerical simulations to describe a convective mechanism that could be considered an alternative to the rising-tube model. They investigated the formation of an active region via the flux rise due to convective motions. The computed scenario does not imply the pre-existence of a coherent flux tube. A uniform, untwisted, horizontal magnetic field is initially present, and magnetic loops subsequently form with a wide range of scales. However, the initial field is required to be relatively strong, and only a moderate magnetic-field amplification (by a factor of about three) can be achieved. Further studies of MHD convection in the context of local dynamo were done, e.g., by Kitiashvili et al. (2013).

It is now clear, however, that Tverskoi's convective mechanism in its original form can hardly describe the actual processes. Without going into details, we only note the following: first, the stability of the convection cell winding the magnetic field lines is completely beyond the scope of the model, although stability is of crucial importance for the efficiency of the mechanism; second, well-developed sunspot groups are typically larger than supergranules.

Nevertheless, Tverskoi's model, if it is modified in some way, appears to be able to catch some important aspects of the processes forming local magnetic fields. It can easily be imagined that especially large and energetic cells sometimes originate in the convection zone and, interacting with the global azimuthal field, *occasionally* give rise to strong bipolar magnetic fields. It is in this respect that they contrast with the ubiquitous "normal" supergranules, which could be expected to produce smaller-scale fields. On the other hand, the convective mechanism can also operate on smaller spatial scales, being responsible for the development of various local magnetic features. It can also act in parallel with the process of magnetic-field-line sweeping.

Some steps were made to modify Tverskoi's mechanism so as to extend its area of applicability. Specifically, simulations of magnetoconvection developing from random initial thermal perturbations were carried out for a domain far exceeding the expected characteristic convection wavelength in the horizontal directions (Getling et al., 2013, see also our Fig. 3). The initial magnetic field was assumed to be uniform and horizontal. At the initial evolutionary stage, a system of cells develops in the form of irregular polygons. It was shown that cellular magnetoconvection can produce bipolar (and also diverse more complex) configurations of a substantially amplified magnetic field. This occurs both in the inner parts of convection cells, where magnetic field lines are "wound" by circulatory fluid motion, and in the network formed by their peripheral regions due to the "sweeping" of magnetic field lines. The topology of the flow plays a fundamental role in the operation of this mechanism, and it can be expected that the basic regularities of the process should manifest themselves in nearly the same way on different spatial scales.

Obviously, the manifestations of the rising-tube and convective mechanisms should substantially differ. The

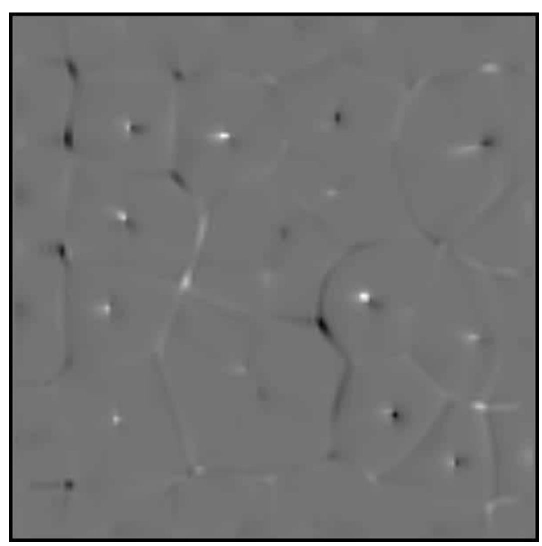

Fig. 3. Gray-scale map of the vertical magnetic-field component, B_z, in a horizontal plane located near the no-slip upper boundary of the computation domain in a simulation run for a Rayleigh number of $\mathrm{Ra} \approx 50\mathrm{Ra_c}$ (where $\mathrm{Ra_c}$ is the critical Rayleigh number), a Prandtl number of $\mathrm{Pr} = 30$, a magnetic Prandtl number of $\mathrm{Pr_m} = 300$ and a Hartmann number of $\mathrm{Ha} = 0.01$ (Getling et al., 2013). The domain measures $8 \times 8 \times 1$. The magnetic field is shown for a time of $10t_\nu$ (t_ν being the time of viscous transfer across the layer); the magnetic-field strengths range from -28.5 to 17.2 (in the units of the initial field strength); at the same time, the field strength at the mid-height of the layer ranges from -116.7 to 162.1.

[2] In this section, we discuss the properties of *toroidal* eddies. Thus, to avoid terminological confusions, we do not use here the commonly accepted term *toroidal magnetic field* and prefer to speak about the global *azimuthal field*.

point is to find observational criteria to distinguish between the action of either of them. With this aim in view, we developed an observational program to study the evolution of both the velocity and magnetic fields in growing active regions. This program (operation plan) is intended for implementation with the SOT on the *Hinode* spacecraft (Tsuneta et al., 2008; Suematsu et al., 2008; Shimizu et al., 2008) and has been designated as HOP181 (<http://www.isas.jaxa.jp/home/solar/hinode_op/hop.php?hop=0181>). It consists in simultaneously recording and subsequently analysing the dynamics of the full-vector velocity and magnetic fields on the photospheric level. We present here some preliminary, purely qualitative results of processing the data obtained at an initial implementation stage of the program.

3. Observations and data processing

A bipolar magnetic structure, which emerged within AR 11313, was observed at its early evolutionary stage, on 9–10 October 2011; the region was then near the centre of the solar disc. Five 2-h-long observational sessions were carried out with intervals that varied from 3 h 40 min to 6 h 30 min.

During each session, a $150'' \times 163''$ field of view was observed using the Narrowband Filter Imager (NFI) of the SOT at two wavelength positions of FeI λ5776 Å with a time cadence of 2 min and a pixel size of $0.16''$. This yielded a series of photospheric images, which can be used to calculate horizontal velocities,[3] and a series of Dopplergrams representing the line-of-sight velocities. Simultaneously, the same FOV was scanned with the Spectro-Polarimeter (SP; see Ichimoto et al. (2008), Lites et al. (2013)) one or two times a session. The SP scan was done in the so-called fast mode with a pixel size of $0.32''$, taking 32 min to obtain one SP map. To derive full-vector magnetic fields from these SP observations, we used the MERLIN inversion code (Lites et al., 2007), which assumed a Milne–Eddington atmosphere. At this investigation stage, however, we did not use data for the line-of-sight velocity and tangential magnetic field.

The processing of the data included:

(1) subsonic filtering based on Fast Fourier Transform;
(2) constructing Dopplergrams;
(3) an intensity-scaling procedure enhancing the image contrast by means of cutting off the tails of a pixel-intensity histogram and subsequent linear mapping of the remaining portion of the histogram onto the whole admissible intensity range;
(4) alignment of the properly rescaled magnetograms with the corresponding images and Dopplergrams;
(5) determination of the horizontal-velocity field using a technique based on the same principle as the standard method of local correlation tracking (LCT) but more reliable (see Getling and Buchnev (2010) for a description) and construction of cork-motion maps. Our technique differs from the standard LCT procedure in a special choice of trial areas ("targets"), whose displacements are determined by maximising the correlation between the original and various shifted positions of the target. Specifically, an area is chosen as a target in a certain neighborhood of each node of a predefined grid if either the contrast or the entropy of the brightness distribution reaches its maximum in this area. The horizontal velocities obtained are then interpolated to the positions of imaginary "corks" using the Delaunay triangulation and affine transformations specified by the deformation of the obtained triangles at the time step considered.

The maps obtained at step (5) represent the trajectories of imaginary "corks" that follow the velocity field inferred from a series of images and attributed, to some approximation, to the material flow. We compared the trajectory maps with the maps of the magnetic field for times close to the mid-times of the corresponding series.

Samples of the maps, which were qualitatively compared, are shown in Fig. 4. For each session, a contrast-enhanced FeI λ 5576 Å image, a cork-trajectory map and a map of the line-of-sight magnetic field are presented. The trajectory of each cork in a velocity map starts with a black dot and terminates at a bright white dot. In most cases, the 2-h length of the session is sufficient for the corks to reach stagnation segments of their trajectories, where the corks no longer move over the photospheric surface. The stagnation segments should obviously correspond to downflow areas in the velocity field.

4. Results

As can be seen from a comparison between the top panels of Fig. 4a and b, a fairly large bipolar sunspot group has already formed in the area under study by the time of the first observational session. At nearly the same time, a new group starts developing between the main spots, in the left half of the field of view. This process becomes mainly accomplished by the third session (Fig. 4b).

The middle panels of Fig. 4a and b represent the velocity field by maps of cork trajectories. To make some features of the flow better distinguishable, the velocity map of Fig. 4a is additionally presented here in an enlarged form in the top panel of Fig. 5 together with a schematic outline of the most pronounced features in the bottom panel, both being plotted on the same scale. In the velocity maps, several areas of local divergent flows apparently

[3] Since the area of interest was located near the solar-disc centre and, moreover, corrections for projection effects are not important from the standpoint of our goal, we do not make difference here between the transversal (tangential) and horizontal vector components and also between the line-of-sight and the vertical component.

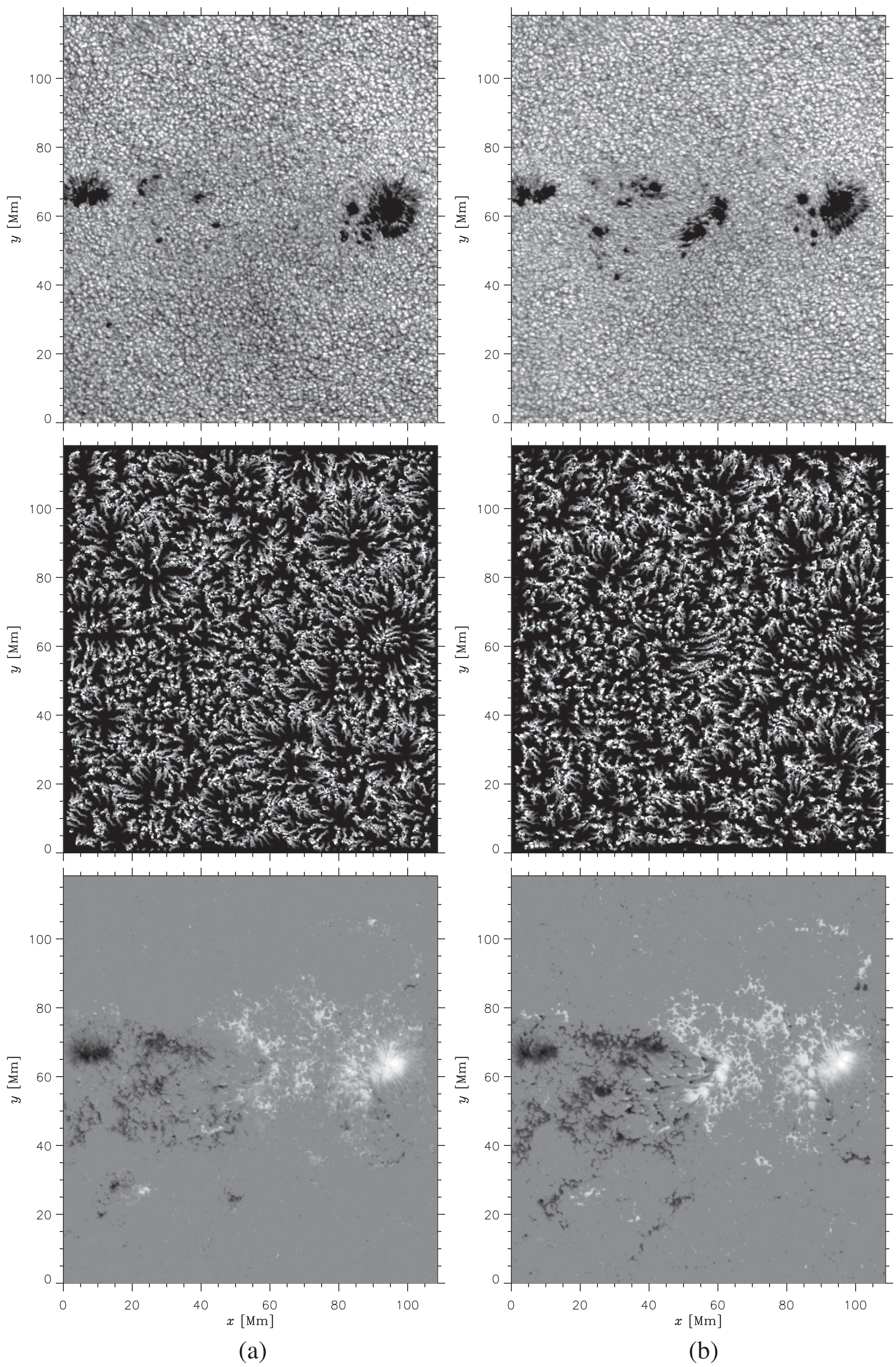

Fig. 4. Comparison of intensity maps (top), horizontal-velocity fields (middle) and line-of-sight magnetograms (bottom) obtained during the first (a) and third (b) observational sessions (at 18–20^{h} of 9 October and 06–08^{h} of 10 October 2011, respectively; the intensity maps and magnetograms were taken at the mid-times of these intervals). The trajectory of each cork in the velocity map starts with a black dot and terminates at a bright white dot. Light and dark areas in the magnetograms correspond to two signs of the magnetic field.

corresponding to supergranules can be identified; four of them are marked with closed short-dashed contours in the bottom panel of Fig. 5. These supergranule-sized flows are very similar in their appearance to “normal” supergranular flows in the quiet photosphere as detected using the same technique (Getling and Buchnev, 2010, Fig. 2).

A careful consideration of the two velocity maps reveals neither any spreading flow on the scale of the developing group nor any flows more intense than normal supergranular convection. This is especially evident from the cork-trajectory map of the first session (middle panel of Fig. 4a and upper panel of Fig. 5), which corresponds to

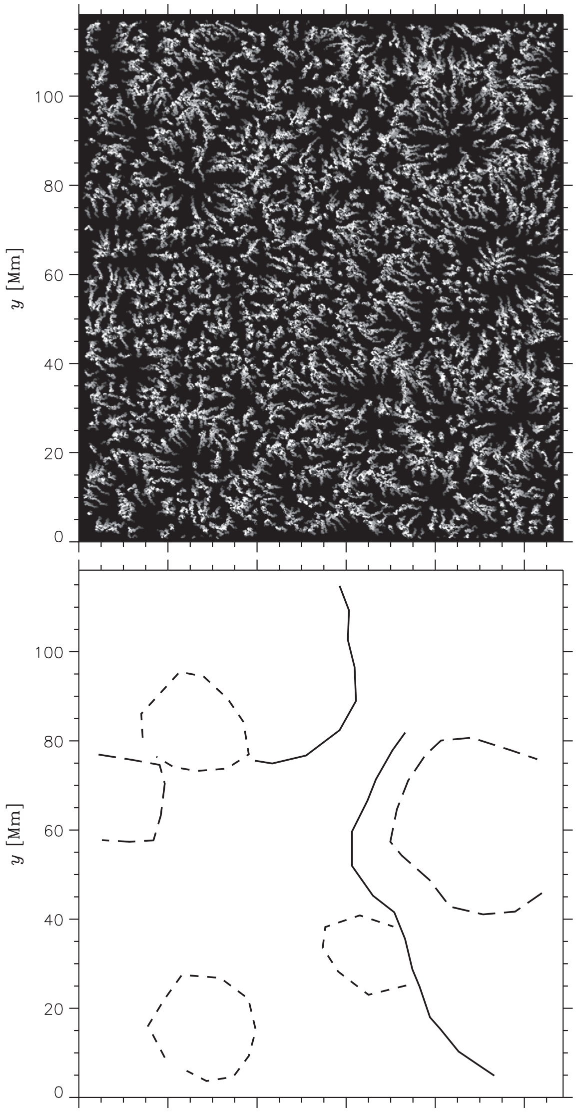

Fig. 5. Top: enlarged map of the horizontal-velocity field shown in the middle panel of Fig. 4a; bottom: schematic outline of some features present in this map, viz., lines of convergence (solid curves), contours of areas occupied by sunspot-related divergent flows (long-dashed curves) and contours of most pronounced supergranules (short-dashed curves).

an early development stage of the new sunspot group. At this stage, a large-scale spreading flow would be well pronounced in the case of the emergence of a strong flux tube. However, no large-scale outflow from the location of the developing group can be found in the map; in contrast, local spreading flows on meso- and supergranular scales unaffected by any large-scale disturbances are observed.

As concerns the maps for the third session (Fig. 4b), a stream seemingly related to the newly formed magnetic feature can be seen in the central part of the middle panel. It issues from the vicinity of the point with coordinates of (50 Mm, 60 Mm) in the middle panel of Fig. 4b, is mainly directed rightward and does not resemble a spreading flow. The magnetogram in the bottom panel of the same figure exhibits faint signs of small-scale cellular structuring of the magnetic field on the left of the field-of-view centre, within the area where the new active processes occur. Such structuring is hardly compatible with the idea of flux-tube emergence. This is additional evidence against the presence of a spreading flow that could be associated with the emergence of an Ω-shaped loop of an intense magnetic-flux tube, all the more so because the emergence process would mainly have terminated by that time.

In the velocity maps, bright curves stretching over long distances can be distinguished, which appear as condensations of the end segments of the cork trajectories approaching these curves from two sides, i.e., as separatrices between oppositely directed flows. Two such conjectural separatrices are shown as solid curves in the scheme of Fig. 5, bottom. Quite likely, they are merely due to aggregate visual effects of centrifugal flows in different supergranules; however, even in this case, this pattern disagrees with the velocity field that could be expected in the case of emergence of an intense flux tube.

Apart from our discussion of the formation mechanisms for strong local magnetic fields, it is interesting that our trajectory maps reveal some details of flow structure related to well-developed sunspots. Although the brightness inhomogeneities in the umbras of the main spots are not distinguishable by eye, they are nevertheless sufficient to visualise the structure of the velocity field. As Fig. 4 indicates, there are flows converging to the umbra centres. At the same time, diverging flows can be seen around these spots.

5. Summary and conclusion

To summarise our qualitative findings, we note that the velocity field in a growing active region has nothing to do with a flow pattern that could be expected if an intense-magnetic-flux tube emerged at the photospheric level. This can be seen from (1) the absence of violent spreading flows on the scale of the entire growing magnetic region, (2) the preservation of normal mesogranules and supergranules, (3) the signs of small-scale structuring of the magnetic field in the area where new spots develop and (4) the signs of the presence of separatrices between polarities, to which material flows converge. In this context, it is interesting to remember some inferences made very long ago.

As Bumba and Howard (1965) wrote, the development of a spot group seems to be controlled by the supergranular network: "the ordered motion within the supergranule is not only strong enough to concentrate weak fields to the outer boundary, but also has sufficient strength and scale to greatly influence the positions of spots that have magnetic fields of at least several hundred gauss. So the supergranular pattern is of fundamental importance in the formation and structure of individual active regions". In particular, the larger spots occupy areas that appear to correspond to one or two supergranules. Furthermore, Bumba (1963) has found that "the photospheric plasma moves approximately along the lines of force of the intense local field". A comprehensive summary of these studies was given by Bumba (1967), who noted that the development of an active region does not involve the destruction of the preexisting convective-velocity field; in essence, the observations demonstrate that the magnetic field coming from below "seeps" through the network of convection cells.

In addition, we revert to the above-mentioned features of magnetic-field evolution observed in the movie of AR 10926 magnetograms (see Introduction and NASA (2007)). Diverging flows may be associated with individual magnetic islands (the "effervescent-tablet" effect) rather than with the whole region.

Our technique also reveals the flow structure in sunspots. Specifically, we managed to detect converging streams in the spot umbras, while spreading streams are observed around the spots.

In conclusion, let us comparatively discuss the consistency of the rising-tube and the convective model with observations. To this end, we list first some points of disagreement between the rising-tube model and observations, based on both the observational data available in the literature and our findings, and then demonstrate how the convective model avoids these difficulties.

- The developing magnetic fields are observed to "seep" through the photosphere without breaking down the existing supergranular and mesogranular velocity field, in contrast to what should be expected if a flux tube rose. In particular, a strong horizontal magnetic field at the apex of the rising loop should emerge on the surface and impart a roll-type structure to the convective flow.
- In contrast to the observed complex patterns of magnetic fields, this strong horizontal field would be a predominant magnetic feature on the scale of the entire active region before the origin of a sunspot group.
- No spreading flows are observed on the scale of the entire complex magnetic configuration of the developing sunspot group, as could be expected in the case of the emergence of a tube. Instead, flows are locally associated with each small-scale magnetic island. In particular, such finely structured flows (the "effervescent-tablet" effect) can be clearly seen in the AR 10926 magnetograms obtained on *Hinode* (NASA, 2007).
- The presence of "parasitic" polarities within the area filled with a predominant magnetic polarity is not accounted for by the rising-tube model.
- The coexistence of differently directed vertical velocities inside the regions of a given magnetic polarity appears to be inconsistent with this model.

In our opinion, the convective mechanism seems to better agree with observational data in view of the following:

- The observed consistency of the developing magnetic field with the convective velocity field is an inherent property of this mechanism.
- Since the amplified magnetic field should largely be collinear with the streamlines, no strong horizontal field should connect different polarities.
- If convection forms local magnetic fields, spreading flows should actually be associated with developing magnetic islands rather than with the entire complex.
- Diverse complex patterns with mixed polarities can be accounted for in a natural way by the presence of a fine structure of the convective flow.
- The convective mechanism can in principle operate on various spatial scales, being controlled solely by the topology of the flow.

Strictly speaking, our inferences from the described observational data may not be quite universal, since we have studied only one evolving sunspot group, which, in addition, developed within an already formed group. Therefore, care must be taken in extending our findings to the overall pattern of MHD processes. Acquisition of more observational information in parallel with further development of data-processing techniques is needed to make more reliable conclusions concerning the formation mechanisms for the photospheric magnetic fields.

Nevertheless, the observational data described here can hardly be interpreted in the framework of the rising-tube model, so that the convective model appears to be more promising in terms of the representation of reality.

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