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

A. V. Getling\textsuperscript{a,}\textsuperscript{*}, R. Ishikawa\textsuperscript{b}, A. A. Buchnev\textsuperscript{c}

\textsuperscript{a}Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, 119991 Russia
\textsuperscript{b}Hinode Science Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 180-8588 Japan
\textsuperscript{c}Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk, 630090 Russia

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 $\Omega$-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 Doppler-grams 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. Instead, normal mesogranular and supergranular flows are observed, and separatrices between the magnetic polarities can be identified, 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

\textsuperscript{*}Corresponding author

Email addresses: A.Getling@mail.ru (A. V. Getling), ryoko.ishikawa@nao.ac.jp (R. Ishikawa), baa@ooi.ssc.ru (A. A. Buchnev)
1. Introduction

The idea that the magnetic field of a bipolar sunspot group originates from the emergence of an \(\Omega\)-shaped flux tube of strong magnetic field already formed in the underlying layers is more and more objected based on both recent, very detailed observational data and current views of the processes in the deep layers. The rising-tube model no longer determines the paradigm in the investigation of the development of local magnetic fields.

First of all, if it is adopted, one has to account for the origin of the strong magnetic field in the tube; to this end, some additional, fairly artificial assumptions need to be introduced. Second, and especially important, is that the evolutionary pattern inferred from this model for local photospheric magnetic fields disagrees with the pattern actually observed on the Sun. We postpone summarising the weak points of the rising-tube model to the conclusive section of our paper but give now only one impressive example of the observed features that do not support this model.

Such an example can be found in the movie showing the so-called solar-“trilobite” magnetogram obtained on the Hinode satellite in December 2006 (NASA, 2007). Although spreading flows related to the emerging magnetic field can be noted in this movie, 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, which resembles the trilobite fossil animal.

Alternatively, the formation of local magnetic fields can be attributed to local processes driven by convection. Such processes belong to the class of mechanisms that are now referred to as local dynamo mechanisms. We shall discuss here only the convective local dynamos.

Tverskoi (1966) was likely the first to suggest a local convective dynamo mechanism. He considered a simple kinematic model describing the formation of a magnetic dipole by a toroidal
eddy in a perfectly conducting fluid. The action of Tverskoi’s mechanism is illustrated in Fig. 2. The fluid particles move in circular trajectories, and the circles of a given radius form a toroidal surface. The magnetic field lines, which are initially straight and horizontal, are wound by the fluid motion around the tori and form two flux concentrations, with oppositely directed magnetic fields, in the central part of the eddy. Tverskoi’s prediction was later qualitatively confirmed by nonlinear numerical simulations, which were carried out for the cases where the flow corresponds to a pattern of hexagonal, Bénard-type cells and is strongly stabilised by the conditions of periodicity in the horizontal directions (Getling, 2001; Dobler & Getling, 2004). In these simulations, a bipolar magnetic structure similar to that found by Tverskoi develops in each convection cell. In addition, the vertical component of the magnetic field is enhanced in the contact zones between the hexagonal cells, i.e., in the intercellular lanes.

Tverskoi regarded the toroidal eddy as a schematic representation of a convection cell. In essence, he demonstrated that the topology of the flow is most important in terms of the MHD effects of convection. He conjectured that supergranular convection cells, interacting with the latitudinal (azimuthal) component of the global magnetic field in nearly the same way as such eddies interact with the horizontal initial field, could be producers of the magnetic fields of bipolar sunspot groups. If so, Tverskoi’s model appears to be as successful as the rising-tube model in terms of agreement with the Hale polarity law and other global properties of solar activity.

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 much 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 subphotospheric layers and, interacting with the global latitudinal 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

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1Since we discuss here the properties of toroidal eddies, we do not use the commonly accepted term toroidal magnetic field to avoid terminological confusions.
can also act 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 find an extended area of possible manifestations of the convective mechanism. 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, Kolmychkov & Mazhorova, 2013, see 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 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 to be implemented with the Solar Optical Telescope (SOT) on the Hinode spacecraft and has been designated as HOP181 (http://www.isas.jaxa.jp/home/solar/hinode_op/hop.php?hop=0181). It consists in simultaneous recording and analysing the dynamics of the velocity and magnetic full-vector 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.
2. Observations and data processing

The object of observations was the bipolar magnetic structure that emerged within AR 11313 during the early evolution of this structure, 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, filtergrams and Dopplergrams in line FeI $\lambda$ 5576 Å were recorded with a time cadence of 2 min and 32-min fast-mode spectropolarimetric scanning was done one or two times. This yielded series of photospheric images, which can be used to calculate horizontal velocities, vertical velocities and all three components of the magnetic field. 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 to the whole admissible intensity range;
4. alignment of the images and Dopplergrams of each series with one another and, after a proper spatial scaling, with the magnetogram;
5. determination of the horizontal-velocity field using a technique based on the same principle as the standard local-correlation-tracking method but more reliable (for a description, see Getling & Buchnev, 2010) and construction of cork-motion maps.

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 $\lambda$ 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.

3. Results

It can be seen from Fig. 4a that a 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).

A careful consideration of the two velocity maps reveals neither any spreading flows on the scale of the developing group, directed from the location of this group, nor any flows more

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2Since 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 tangential and horizontal vector components and also between the line-of-sight and vertical components.
intense than normal convection. For example, although the stream that issues from the vicinity of the point with coordinates of approximately (50 Mm, 60 Mm) in the right-hand map (mainly directed rightward) seems to be related to a newly formed magnetic feature, it does nevertheless not definitely exceed in its speed the flows in the supergranules centred at about (20 Mm, 80 Mm) and (85 Mm, 90 Mm) in both maps and in the supergranule centred at about (60 Mm, 90 Mm) in the right-hand map. At the same time, the mesogranule with a centre near (40 Mm, 50 Mm) seen in the right-hand map has a fairly regular appearance and does not seem to be affected by the above-mentioned stream. Moreover, an imprint of convection cells can easily be detected in the right-hand magnetogram, on the left of its centre, within the area where the new active processes occur. Therefore, there are no signs of a spreading flow that could be associated with the emergence of an Ω-shaped tube of intense magnetic flux. The development of the new active region does not destroy the already formed pattern of supergranular and mesogranular velocities.

Another remarkable feature present in the velocity maps should also be noted. In the middle rows of both Fig. 4a and Fig. 4b, 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. They are not quite regular and quite continuous but, despite interruptions, intersect (mainly vertically) the entire field of view. Apparently, streams converge to these curves, which are separatrices between oppositely directed flows. The pattern of this convergence obviously changes as the active region evolves; however, if the emergence of a flux tube of strong magnetic field occurred, it would anyway appear as material spreading from the emergence site, noticeable during the same time interval. Even if the convergence curves are merely due to aggregate visual effects of centrifugal flows in different supergranules, this pattern is hardly compatible with the velocity field that could be expected in the case of emergence of an intense flux tube.

The sequence of filtergrams of the second session (not shown here) demonstrates an intense local mesogranular-scale spreading in an area around the point (40 Mm, 50 Mm). However, it is not related to the formation of a bipolar magnetic configuration but leads only to a concentration of magnetic field in the intercellular lanes and to the formation of a cellular magnetic pattern (seen in the magnetogram of the third session, Fig. 4c). Therefore, this is a case where neither the rising-tube mechanism nor the convective mechanism proves to be efficient.

Apart from our discussion of the formation mechanisms for strong local magnetic fields, it is worth observing 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 visually undistinguished, 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.

4. Summary and conclusion

To summarise our qualitative results, we note that the velocity field in a growing active region has nothing to do with a flow pattern that could be expected in the case of emergence of a rising intense-magnetic-flux tube. This can be seen from the absence of violent spreading flows on the scale of the growing magnetic field, from the preservation of normal mesogranules and supergranules in the area where the magnetic field develops and from the presence of separatrices between the polarities to which the material flows converge rather than diverging from them. In contrast, diverging flows may be associated with individual magnetic islands (the “effervescent-tablet” effect) rather than with the whole region. The observed evolutionary scenario agrees with
the inference made very long ago by Bumba (1967) that the development of an active region does not involve the destruction of the pre-existing convective-velocity field, and the magnetic field coming from below “seeps” through the network of convection cells.

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

In conclusion, let us comparatively discuss the compatibility of the rising-tube and the convective model with observations. To this end, we list here 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 points.

• 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 well-known “trilobite” magnetogram 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 proves to be better compatible 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.
Figure 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 18–20h of 9 October and 06–08h of 10 October 2011, respectively). 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.
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 the data-processing procedures 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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