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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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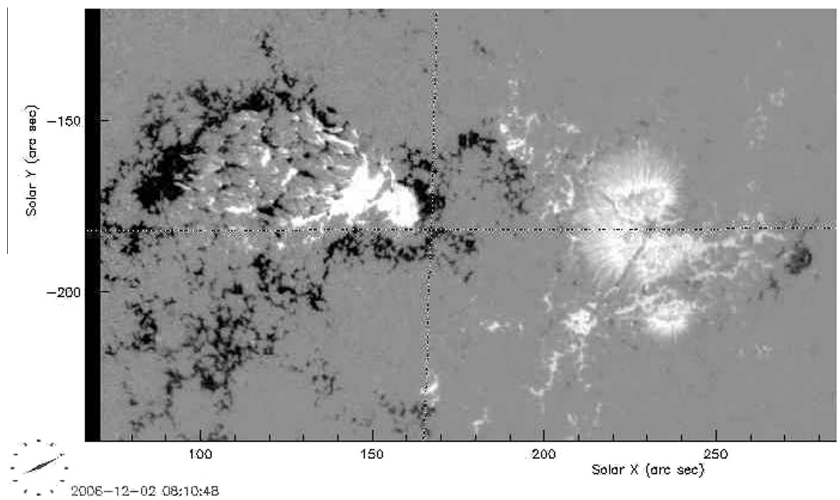


Fig. 1. Fragment of a line-of-sight (Stokes V) magnetogram of AR 10926, where a sunspot group is developing. The magnetogram was obtained on 2 December 2006 at 08:10:48 UT with the Solar Optical Telescope on the *Hinode* satellite. Black represents negative polarity, and white represents positive.

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).