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A model for magnetic flux transport

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Abstract. One of the most noticeable manifestation of Sun's variable activity consists in the increasing and decreasing number of active regions covering the solar photosphere throughout each cycle. Active regions are thought to be the product of the emergence of buoyant flux tubes formed at the base of the convectione zone; once emerged, their cross sections with the photosphere are observed as magnetic concentrations forming active regions. We present a model in which the evolution of a bipolar magnetic structure is due to the advection of magnetic flux elements by a field characterized by spatio-temporal correlations mimicking granulation and supergranulation scales observed on the photosphere. At this stage we can only take into account the effects of diffusion and impingement, from the appearance of magnetic flux concentrations to their dissolution. The inclusion of such a model into full-Sun simulations, also including large scale effects such as differential rotation and meridional flows, might be useful not only for studying variability and the solar cycle, but also for the investigation of Sun-like stars luminosity and radial velocity fluctuations, observed for example by Kepler mission, in order to investigate the impact of stellar magnetic activity on the detection of exoplanets.

Key words. Sun: photosphere – Sun: magnetic field

1. Introduction

Solar activity is characterized by an 11-year cycle, whose most evident manifestation consists in the variation in number of magnetic features, such as sunspot and active regions, observed on the solar surface throughout each cycle. The patterns in which those large-scale magnetic structures emerge are found to be regular and cycle-dependent. At cycle maximum, defined as the period in which sunspots cover the largest fraction of the solar surface, active regions emerge at about 30° in latitude, with the leading part closer to the equator, according to Joy's rule, and the emergence latitude decreases throughout each cycle, to reach values of about 10° at cycle minimum. Bipolar active regions appear according to Hale's polarity law: the leading and trailing parts of the active regions have opposite polarities, and the polarity reverses in the two emispheres and in following cycles. Together with those large-scale fluxes, associated with sunspots and bipolar active regions, there is a great number of smaller magnetic features, which cover most of the solar surface. Those small scale elements are more mobile than the large-scale ones, and seem to follow the same trends in their emergence patterns, even if with larger statistical variation. Once emerged, all those magnetic structures are diffused due to the presence of differential rotation and meridional flows on the largest scales,

while at smaller scales motions associated with granulation and supergranulation act in the direction of confining the magnetic elements in the intergranular lanes. A realistic model of flux transport on the photosphere, including the effects of differential rotation, meridional flows and convective motions associated with granulation and supergranulation, should take into account how large and small scale structures' evolution couple to produce the effects of inversion of the Sun's magnetic field and its intensity on the photosphere.
Schrijver (2001) and De Rosa (2006) propose a flux transport model in which the diffusion of small scale magnetic elements occurs according to a random walk, in which the mean-free-path depends on the magnetic field carried by each element, thus reproducing the evidences according to which small scale flux appear more mobile than large scale ones.
In this work we present a model in which the diffusion of the small scale elements is due to the presence of an advection field characterized by spatio-temporal correlations reflecting those of granulation and supergranulation. The inclusion of such a field in a full-Sun model might be of interest not only for what concerns strictly the physics of the Sun, but also to investigate the impact that convective motions on the surface of Sun-like stars have on the detectability of exoplanets.

2. The Model

At present computational capabilities are not sufficient for the implementation of MHD equations to determine the evolution of the Sun's magnetic field on an extended region of the Sun. It is thus necessary to formulate kinematical models in which, for example, a certain region of the Sun is represented on a bidimensional grid. Such models are able to produce consistent datasets, fitting with the observations, and thus allow to understand the physical phenomena which control the evolution of the observed structures. In this work we present a model in which the evolution of a bipolar active region is due to the presence of an advection field, characterized by spatio-temporal correlations typical of granulation and supergranulation. The model (Berrilli, Del Moro, Viticchié, 2008) was developed in a way similar to the one proposed by Rast (2006), according to whom the scales of mesogranulation and supergranulation are produced by the collective interaction of advection fields generated by granular downflows.
The model discussed here is able to reproduce the evolution of a bipolar active region from its appearance to its dissolution: the magnetic elements which constitute the two polarities of the active region are passively carried by the advection field, which is generated as follows:

- The downflow plumes are randomly distributed on the computational domain, with an amplitude gaussianly distributed with mean 1 and standard deviation 0.5 (in units of 1 km/s)
- The computational domain is periodic in all directions, and the amplitude of the advection field associated with each plume is truncated at a distance from its source equal to half the dimension of the domain
- The amplitude of each plume decays esponentially with a decay constant 10 (in units of 0.2 hr). If the amplitude of the velocity field associated to a plume decreases under a threshold value, set to 0.0001, that plume is removed from the domain
- The time evolution of each plume in the domain is due to the collective field generated as the vectorial sum of the advection fields associated to all the other plumes.
- When the distance between two downflow plumes goes under a critical value,chosen as one resolution element, the two interacting plumes are replaced by a single plume whose position is determined as the weighted average of the positions of the interacting plumes, the weights being the associated amplitudes, and whose amplitude is taken as the sum.
- The time step of the simulation is determined as half the ratio between the minimum distance separating two plumes and the maximum velocity on the domain.

The spatial and temporal scales mentioned here are referred to the granulation scales. With a

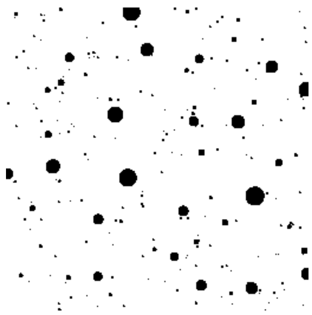

Fig. 1. Advection field in its stable configuration. The size of the circles is proportional to the intensity of the downflows. The system reproduces the spatio-temporal correlations of granulation, mesogranulation, supergranulation observed on photosphere.

suitable choice of the parameters of the simulation the system is able to produce, starting from the interaction of fluxes on the granular scale, stable structures which organize themselves on the scales of mesogranulation and supergranulation. Fig. 1 shows the advection field in its stable configuration, and the size of the circles is proportional to the local intensity of the advection field. After the system has reached its stable configuration, a bipolar active region is injected in the domain. The active region's barycenter is located in the region of the domain in which the velocity field is minimum, and its evolution is only determined by the presence of the advection field. The magnetic elements are passively driven by the horizontal velocity field due to the presence of the downflow plumes. In particular:

- To each magnetic element is associated a field equal to 30G
- The velocity with which the elements are transported by the advection field is proportional to the number of neighbours surrounding the element. As a result, the outermost elements of the active region are carried more efficiently, while the inner one are more stable,and a mechanism of boundary erosion is simulated
- When two magnetic elements converge in the same position in the domain, they are replaced by a magnetic element at the same position whose magnetic field is the vectorial sum of the interacting fields
- The interaction between two elements can not produce fields with a value greater than 2000G, which is the maximum value that the magnetic field of an isolated structure can reach in conditions of equilibrium with the surrounding plasma

As the simulation goes on the bipolar active region decays under the action of the advection field, giving rise to diffuse magnetic structures whose field is determined by the interaction between the decay products of the bipolar active region. We report in Fig. 3 the bipolar active region at different time steps of the simulation. Starting from two magnetic concentrations of opposite polarities, under the action of the advection field, the system reaches a configuration in which the magnetic field is preferentially diffused in the regions of the domain where the velocity field is more intense.

3. Conclusions

The present model is able to reproduce the evolution and decay of a bipolar active region under the action of an advection field characterized by spatio-temporal correlations of granulation, mesogranulation and supergranulation. What is referred to as dynamo problem consists in finding the conditions under which the observed fluxes would be able to sustain the cyclic rigeneration of the magnetic field associated with the solar cycle. According to the so-called Babcock-Leighton model, large scale flux transport occurs thanks to differen-

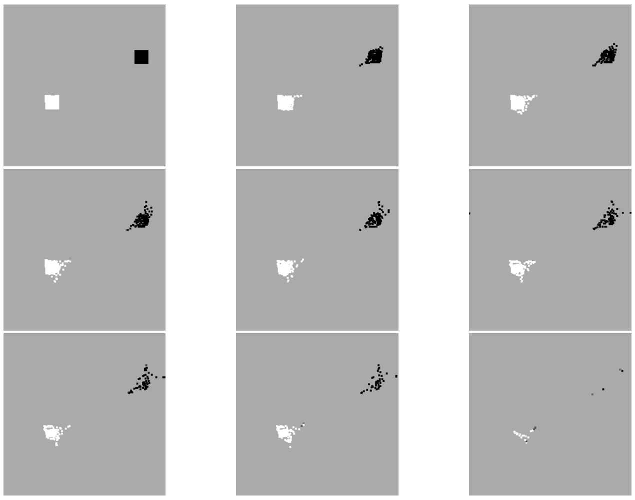

Fig. 2. Bipolar active region at subsequent time steps of the simulation. At the initial state the magnetic field is concentrated in the regions of the domain where the active regions are located. Under the action of the advection field the magnetic elements are diffused in the region where the velocity field is stronger

tial rotation and meridional flows. Together with those large scale fluxes, convective motions on the granular scale confine small scale magnetic elements in the intergranular lanes. Schrijver(2001) and De Rosa(2006) propose a model in which the small-scale flux transport is simulated by a random walk, in which the mean-free-path depends on the field associated to the magnetic elements. Our aim is to replace in a full-Sun model, also taking into account large-scale transport flux, the random-walk proposed by De Rosa with the advection field presented in this work. This may have implications not only for what concerns the understanding of the processes which govern solar activity, but also for the study of the impact that stellar activity has in the detection of exoplanets. Makarov(2010) estimates that the variation in the number of sunspot which cover the photosphere produces an intrinsic scatter in the Sun's radial velocity of the order of 7 m/s correlated with the solar cycle, with a scatter of 1.44 m/s. He also suggests that convective blueshifts associated with granulation may produce scatter on time-scales of a few hours. The inclusion of an advection field characterized by spatio-temporal correlations of granulation, supergranulation and mesogranulation may thus provide useful information in order to separate the effects on radial velocity measurements of planet transits from those due to stellar magnetic activity.

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