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Simulation of atmospheric magnetic reconnections via a dynamic model of photosphere

B. Viticchié, D. Del Moro, F. Berrilli and A. Egidi

Physics Department, University of Rome Tor Vergata
e-mail: berrilli@roma2.infn.it

Abstract. We present a dynamic model of atmospheric magnetic field in which magnetic loop footpoints are advected by a velocity field computed using a simple *n*-body simulation and reproducing large spatial organization scales (e.g. mesogranulation). In this numerical simulation, the advection of passive magnetic elements triggers reconnection processes (occasionally multiple ones) forcing magnetic field reconfigurations and ensuing fluctuations of total magnetic energy. Our simple model reproduces a system with scale-free properties and provides probability distribution functions for emitted magnetic energies described by a power-law index $\alpha \sim 2.4$.

Key words. coronal heating – magnetic reconnection – flare

1. Introduction

Solar flares are energetic events in the solar atmosphere. A single flare can release a great amount of energy ($\sim 10^{30}$ erg). The released energy is stored in the atmospheric magnetic field, which, via magnetic reconnections and rapid reconfigurations, is able to emit magnetic energy explosively in very short time intervals (few min).

The frequency distribution of the peak flare energies obeys a power-law over several orders of magnitude with a robust power-law index. The distribution of quiescent times between different flares obeys time-dependent Poisson statistics for short intervals while for long intervals a power-law tail is found; this kind of distribution is reproduced well by a Levy function (Wheatland & Litvinenko, (2002); Lepreti *et al.*, (2001)).

Here we propose a dynamical model for the atmospheric magnetic field which is represented by circular loops. Each loop is anchored to a two-dimensional domain representing the photosphere. Two footpoints define where each magnetic loop enters the photosphere. Footpoints are transported by a velocity field which presents correlations in space and time. In fact, velocity fields produce mesogranular flows by the interaction of small-scale, short-lived flows that represents granular flows. Loops are driven by the movement of footpoints, moreover they can interact via magnetic reconnection. Multiple magnetic reconnections cause magnetic field configurations to change, from this follows a variation of the magnetic energy of the system.

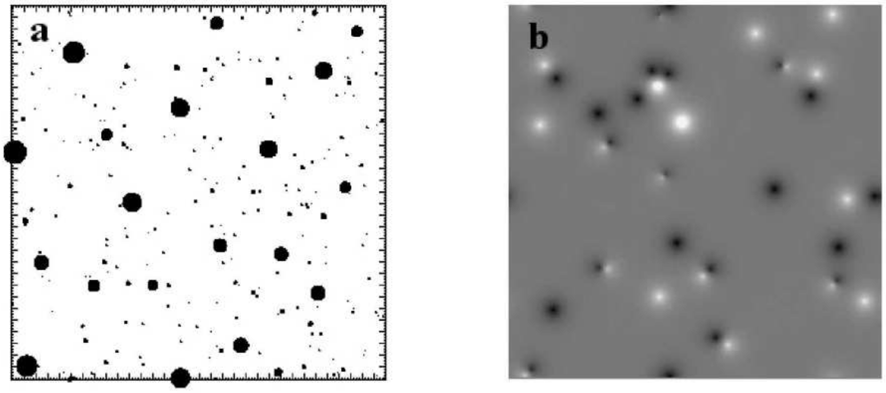

Fig. 1. (a) Pattern of downflows (filled dark circles). The downflow intensity is proportional to the circle dimension. (b) Magnetic concentrations in grey-scale; white regions are positive ones while black regions are negative ones.

2. Photospheric velocity field

We briefly describe the dynamical model for the photospheric velocity field defined on the basis of the model from Rast (2003).

The model realizes the advection-interaction between downflows in a $L \times L$ domain ($L = 256$ pixel) with periodic boundary conditions. We start our simulation with a fixed number, $N = 1000$, of downflows randomly located in the domain. The interaction (attraction) velocity between two downflows follows an exponential law $v = v_0 \cdot \exp \frac{-d}{\sigma}$ (Rast, (1995), (2003)). The decay length for the interaction, σ, is a free parameter. The velocity of a downflow is defined as the sum over all the velocity due to the interactions with other downflows. A process that can vary the number of downflows is the fusion of two downflows that are a unit of length (1 pixel) from each other. In this process we define a new downflow placed in the same position of the strongest downflow. The intensity of the new downflow is defined as the sum of the intensity of the interacting downflows. We suppose that where the downflow is located we have a vertical (orthogonal to the domain) flow velocity equal to v_0. We also suppose that the sum over all the vertical velocities is always equal to the initial sum which is equal to 1000 flow units.

From a statistical analysis (Berrilli *et al.*, (2003)) of downflow baricenter clustering results a granulation length scale $m_G \sim 20$ pixel and a mesogranular length scale $m_M \sim 82$ pixel. The ratio of the length scales is $\frac{m_M}{m_G} \sim 5$ in agreement with the observations. A typical pattern of downflows is reported in Fig.1.a.

3. Dynamic model for the magnetic reconnections

The dynamic model for the magnetic reconnection was defined referring to a model from Hughes *et al.* (2003). The magnetic field is represented by semicircular loops anchored by two footpoints, of opposite polarity, on the same domain $L \times L$ used for the photospheric velocity field. The photospheric horizontal velocity field moves the footpoints driving the magnetic field loops that can interact and cause magnetic reconnections, sometimes multiple ones. In agreement to the model from Hughes *et al.* (2003) we assume the magnetic energy of a single loop proportional to its length. Therefore, the variation of the total magnetic energy of the system, due to a reconnection process, is proportional to the variation of the

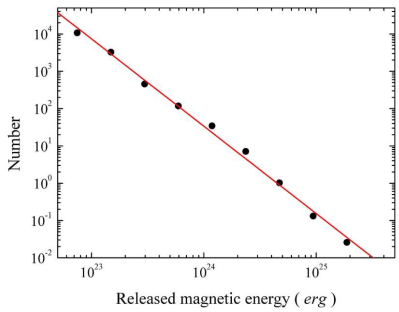

Fig. 2. Frequency distribution for released magnetic energies. Error bars have the dimension of the dots.

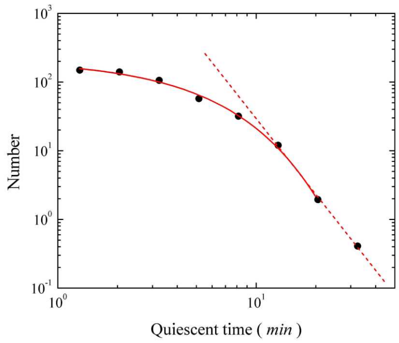

Fig. 3. Frequency distribution for quiescent time between magnetic energy released. Error bars have the dimension of the dots. Solid line represents the exponential fit; dashed line represents the linear fit.

sum over all loops lengths. In Fig 1.b an example of photospheric magnetic field is reported.

Respect to the original model (Hughes *et al.*, (2003)) we implemented new features: *i*) we used the photospheric velocity field (ref. section 2) presenting correlation in space and time in agreement with the observations; *ii*) boundary conditions are periodic; *iii*) in our model loops interact at finite distance. Simulations start in a random configuration with a fixed number of magnetic loops and admit two types of magnetic interactions.

1. interaction between footpoints on the $L \times L$ domain. Footpoints with opposite polarity, from two different loops, can annihilate when they are a unit of length (1 pixel) from each other. After the interaction a new loop is defined between the two remnant footpoints of opposite polarity. Footpoints with the same polarity can aggregate in the same position in the domain.
2. interaction between loops over the $L \times L$ domain. The interaction starts when the distance between the loops is less than or equal to 1 pixel. This interaction causes a reconfiguration of the magnetic field between the involved footpoints.

Magnetic interactions, instantaneous in our model, always cause a release of magnetic energy. If more interactions can take place simultaneously, we start the reconnection process from the interaction that causes the greater emission of magnetic energy.

In our simulations, reproducing the emergence of small scale magnetic fields with a constrain on the minimum dimension for magnetic loops, loops are introduced with a fixed rate during the evolution.

The aim of the simulations is to investigate computed frequencies distributions both for energy emission, due to sequences of magnetic reconnections, and frequencies distribution, for quiescent times between different emissions.

4. Statistical analysis and conclusions

The statistical analysis of magnetic energy emissions over 8 simulations brings us the results presented in Fig. 2:

More in detail, the frequency distribution is well approximated by a power-law over three decades of energy, the index is equal to 2.4±0.1 in agreement with observations of nanoflares (e.g., Krucker & Benz, (1998); Parnell & Jupp, (1999)). In Fig. 3 we report the frequency distribution for quiescent times. For small time interval the distribution is well approximated by an exponential function. For times greater than 10 min we found a deviation from the exponential behavior and the distribution seems well-matched by a power-law. The fit, done on the last three points, needs to be extended in time simulation to define a statistical behavior for large quiescent times. Our approach indicates that this class of dynamical models including space-time correlations in the photospheric velocity field can reproduce both energy and waiting time frequency distributions of nanoflares. Fairly sophisticated numerical simulations may be necessary in order to improve our model and confirm our insights.

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