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Correlated flares in models of a magnetized "canopy"

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Abstract

A model of the Lu–Hamilton kind is applied to the study of critical behavior of the magnetized solar atmosphere. The main novelty is that its driving is done via sources undergoing a diffusion. This mimics the effect of a virtual turbulent substrate forcing the system. The system exhibits power-law statistics not only in the size of the flares, but also in the distribution of the waiting times.

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1. Introduction

One of the most interesting properties of spatially extended dynamical systems in nature is that they can exhibit critical behavior. That terminology loosely derives from the theory of phase transitions in equilibrium statistical mechanics but has come to mean more generally that the system manifests power-law statistics in its characteristic space-time distributions. There may be long range or long term correlations and the structure of fluctuations could have very nonlocal features.

There is so far no general theory dealing with critical behavior for general nonequilibrium systems. At this moment certain schemes are tried, even for some aspects seemingly unrealistic ones, and it is hoped that they retain some general validity when confronted with a larger circle of phenomena. One of the attempts for describing in a more unified way nonequilibrium and dynamical power-laws has been called self-organized criticality (SOC) [1–4]. Normally SOC may be expected in slowly loaded extended systems with local instabilities evolving according to a threshold dynamics, namely being active only when some level of "stress" is larger than a threshold. Local instabilities may trigger further ones upon relaxing, generating avalanches of relaxation that bring the system from a metastable state to another. The occurrence of scale-free avalanches

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has been well documented in cellular automata, often named sandpiles, which provide a surprisingly simple way of simulating SOC [1–4]. The scale-invariant distribution of avalanches in sandpiles is the hallmark of SOC, and it is a robust feature, suggesting that avalanching processes can be a valid explanation of several natural scale-free phenomena [2]. For example, one can argue that the power-law distribution of the energies released by earthquakes or by solar emissions are due to the avalanching nature of these processes.

The present paper revisits some earlier attempts of modeling the critical state of the solar atmosphere via SOC models. The atmosphere of the Sun is very complex and inhomogeneous. Even though there are a growing amount of data concerning solar flare activity, e.g. in Refs. [5,6], we still lack detailed information about statistical-topological aspects. The spatial and temporal resolution of the observation are too ''rough'' for the detection of the small scale structures of the solar atmosphere participating in the considered processes at either photospheric, chromospheric or coronal levels. Various first questions have not been answered. For example, the manifest dynamical features of the solar activity or the mechanisms of heating of the outer atmosphere have not been resolved to a sufficient degree. However, it is believed that the heating and the eruptive phenomena in the solar atmosphere are related to magnetic structures that are constantly being driven and that dissipate via reconnection and wave mechanisms [7] (see also recent new developments reported in Refs. [8,9]). While simplified models must obviously be treated with caution, they can also be welcomed as highlighting single essential features.

The relevance of SOC models for the study of the solar atmosphere has been realized since the pioneering work of Lu and Hamilton [10] (see also Ref. [11]). We will refer to it as the LH-model. The idea was to develop a cellular automaton model for the solar atmosphere that would realize some of the heuristics and of the ideas stated (i) in Refs. [12,13] that solar flares might represent a cascade of smaller events of magnetic reconnection and (ii) in Refs. [14,15] that in the coronal heating a big number of small non-thermal events could make a significant contribution. These works initiated investigating whether cascades of small size dissipations of the magnetic field can avalanche in solar flares to support the observed dynamics and heating rate of the solar atmosphere. The LH-model indicated that under certain conditions for a 3D domain that is slowly ''fed'' by the magnetic field, the system evolves into a critical state showing power-law statistics in the energy released by avalanches (flares).

While these first attempts in the context of the solar atmosphere had opened the possibility to model SOC events under coronal conditions, there were also several and significant limitations. As was pointed out in Ref. [16–19], the LH-model faced some difficulties. For example, there was a problem with the correct physical interpretation of the applied magnetic field. On the other hand the latter authors suggested to consider a large 2D domain, which is uniformly fed by sources of different type and topology. Moreover, it has been emphasized ever since [20] that the LH-model and other sandpile models have time series with exponentially separated events. Hence, they do not reproduce real waiting time probability distributions. That obviously has casted doubts on whether the concept and modeling of SOC is useful at all for studying the dynamical processes in the solar atmosphere.

Recently in Ref. [21] it has been suggested that the basic reason for the unrealistic temporal statistics of some sandpiles comes from the feeding uniformly randomized in space and time. Indeed, this feature is likely to be artificial in several contexts. For example, earthquake epicenters are clustered in space and time. Thus, it appears natural that SOC models will not display clustering and correlation of events in time when a randomization in space of the ''epicenters'' is forced by the chosen driving. A new sandpile cellular automaton was devised having a more natural feeding mechanism, namely a feeding associated to the position of a random walker, mimicking the spatial correlations of diffusing epicenters. The result was a time series with correlated avalanches [24], in particular with power-law tails in the waiting time distributions, which also collapse onto a single scaling function when rescaled by the rates of events, as found for earthquakes [25,26] and solar flares [27].

Existing SOC models imply a rather simplified configuration of the magnetic fields and of the external drivers supporting the system. Moreover the updating mechanisms are only qualitatively representing some of the very complex magnetic dynamics. While we continue in the same SOC-tradition of mathematical modeling, we add here the novel feature discussed above, namely the diffusing feeding sources. Thus, they are not fixed in space nor do they jump from one site to another in an absolutely random way, but they perform a random walk motion, which is the prototype of a correlated evolution in space and time. In the present work