Acceleration and Radiation Model of Particles in Solar Active Regions

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Abstract. Cellular Automata (CA) models have successfully reproduced several statistical properties of solar flares such as the peak flux or the total flux distribution. We are using a CA model based on the concept of self organized criticality (SOC) to model the evolution of the magnetic energy released in a solar flare. Each burst of magnetic energy released is assumed to be the consequence of a magnetic reconnection process, where the particles are accelerated by a direct electric field. We relate the difference of energy gain of particles (alpha particles, protons and electrons) to the magnetic energy released and we calculate the resulting kinetic energy distributions and the emitted radiation.

Keywords: Sun: Solar flares; particle acceleration; radiation; self-organized criticality
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INTRODUCTION

During the last two decades, due to the existence of several space-born solar instruments and of a number of ground based solar telescopes, a number of statistical studies of the solar flaring activity has been performed (see e.g. Vilmer 1993; Vilmer & Mackinnon 2003, for reviews). These observations (Dennis 1985; Benz 1985; Benz & Aschwanden 1992; Crosby et al. 1993; Aschwanden et al. 1995; Crosby et al. 1998; Krucker & Benz 1998; Aschwanden et al. 2000) established that the frequency distributions of impulsive events (in particular solar flares) as a function of total energy, peak luminosity and duration are well defined power laws, extending over several orders of magnitude. Several qualitative models have been developed in order to model the dynamic evolution of solar flares (for reviews see van den Oord 1994; Vlahos 1996; Bastian & Vlahos 1997) following the above observational evidence. These models revealed the necessity to study and understand the global behavior of the evolution of the complex active regions and particle acceleration in such a complex environment.

In order to study the evolution and the dynamics of complex active regions two different approaches can be used: a) MHD numerical simulations (e.g. Galsgaard & Nordlund 1996; Einaudi et al. 1996; Dmitruk et al. 1998; Georgoulis et al. 1998; Galtier & Pouquet 1998; Walsh & Galtier 2000). b) Cellular Automata (CA) models either based on Self Organized Criticality (SOC), (e.g. Lu & Hamilton 1991; Lu et al. 1993; Vlahos et al. 1995; Georgoulis & Vlahos 1996; 1998) or in percolation theory (i.e. probabilistic CA models) (e.g. MacKinnon et al. 1996; MacKinnon & Macpherson 1999; Vlahos et al. 2002).

Both, MHD simulations and CA models, have advantages and disadvantages, but they

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are complementary approaches. Several efforts have been done to find a connection between them. Isliker et al. (1998; 2000) revealed the role of several components of CA models, such as the physical interpretations of the grid-variable, the nature of the energy release process and the role of diffusivity. These efforts leaded to a construction of a new type of CA models for solar flares (Isliker et al. 2001) which are compatible to MHD theory and produce statistical results in agreement with the observations. In addition to the above efforts, hybrid models, which are intermediate between CA models and full MHD and reduced MHD models, have been constructed mainly to account for the coronal heating problem (e.g. Einaudi & Velli 1999; Buchlin et al. 2003).

The approach used for particle acceleration models proposed for solar flares (for review on acceleration models see Miller et al. 1997; Anastasiadis 2002) usually is based on the decoupling of the different processes (i.e. energy release, acceleration, transport and radiation). It is clear that in order to construct global models for solar flares, one must consider the coupling between these different processes. The different time and spatial scales of the processes and the fact that usually are acting simultaneously, make the coupling not an easy task to do (see Cargill 2002 for discussion of coupling models).

In previous studies, Anastasiadis and Vlahos (1991; 1994) proposed a model for the acceleration of particles (electrons and ions) by an ensemble of shock waves, assuming that the energy is released by means of many localized, small - scale explosive phenomena which were the drivers of a number of shock fronts (small - scale, short - lived discontinuities). In these early models there was still a vague and only qualitative association between the acceleration mechanism and the energy release process.

Anastasiadis et al. (1997; 2004) tried to connect the energy release process with the acceleration of electrons in solar flares, using a CA model for the energy release. The acceleration was based on a random number of localized electric fields (super-Dreicer electric fields) closely associated with the energy release process. The goal of the present work, is to improve and extend the above models, calculating in a more consistent way the electric fields and incorporating the radiation process.

THE MODEL

We assume that the observed complexity of a flaring active region and the turbulent driver, which represents the photoshpere, can give birth to multiple Reconnecting Current Sheets (RCS) as a result of magnetic reconnection processes, occurring during the energy release process (for details on magnetic reconnection see Priest & Forbes (2000)). For the study of the energy release process in the active region we use a CA model, and for modelling the acceleration of particles we consider the super-Dreicer electric fields associated with the RCS.

The CA model for energy release

We use a 3-D Cellular Automaton (CA) model based on the Self - Organized Criticality (SOC). The basic idea is that the evolution of active regions can be simulated by the continuous addition or change of new magnetic flux on the pre-existing magnetic

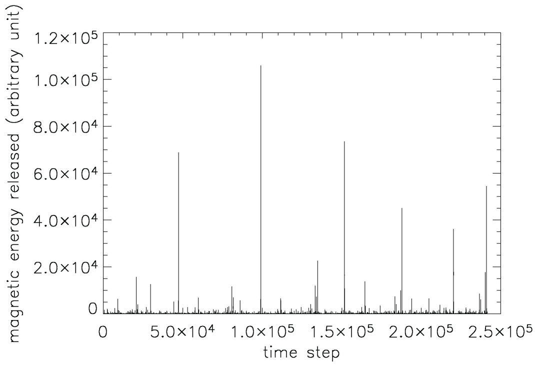

FIGURE 1. The energy release time series for the cellular automaton model. Note the intermittent nature of the released energy.

topology, until the local magnetic gradient reaches a threshold. At this point the local unstable magnetic topology is relaxing by rearranging the excess magnetic field to its nearest neighbors. This redistribution of the magnetic field can cause the lack of stability in the neighbors and the appearance of flares in form of avalanches in all scales of our system. In the following we only outline the basic rules of the CA model, for a detailed description see Vlahos et al. (1995), Isliker et al. (1998) and Georgoulis & Vlahos (1998).

The basic rules of the CA model are:(1) Initial loading (2) Ongoing random loading with increment δB given by the equation:

$$prob(\delta B) \approx (\delta B)^{-5/3} \tag{1}$$

(3) Relaxation process due to reconnection of magnetic field, leading to the generation of Reconnecting Current Sheets (RCS), according to the equation:

$$\vec{\nabla} \times \vec{B} \approx \vec{J} \tag{2}$$

(4) The energy release is calculated using:

$$\varepsilon \approx \left(B_i - \frac{6}{7} B_{\mathrm{cr}} \right)^2 \tag{3}$$

where B_i is the value of the magnetic field of given grid point i, which is becoming unstable when $B_i \geq B_{\mathrm{cr}}$, with B_{cr} being a critical value of the magnetic field.

The most important result from the CA model, for our purpose, is that an energy release time series ($\varepsilon(t)$) can be constructed, using Eq. 3. This time series (see Fig. 1) is highly intermittent, obeys a double power-law frequency distribution, and also exhibits a scale-invariant behavior, enclosing a self - similar nature.

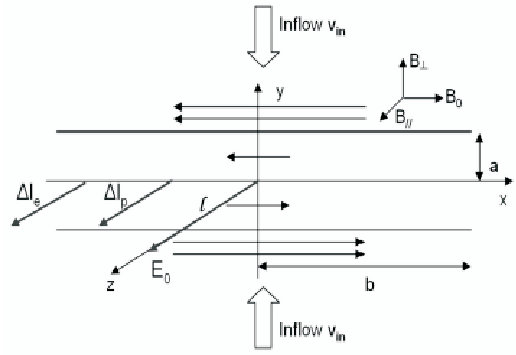

FIGURE 2. The assumed geometry of each Reconnecting Current Sheet (RCS).

The acceleration model

The simplest way to accelerate particles is by a large scale quasi-static electric field. A number of acceleration models with sub-Dreicer electric fields have been proposed for the case of solar flares (see e.g. Tsuneta 1985; Holman & Benka 1992). These models can explain the bulk energization of electrons up to 100 keV, but they are facing several problems such as: the requirement of a very long electric field parallel to magnetic field or the existence of highly filamented current channels, causing current closure and particle escaping problems. Application of super-Dreicer electric field models to solar flares have been also carried out in the past (e.g. Martens 1988; Litvinenko 1996; 2000). These models invoke a RCS with a significant magnetic field, which, together with the assumed inflow plasma velocity, can produce a convective electric field of a super-Dreicer value.

In our model we are following the above approach of the super-Dreicer electric field models. We assume that each energy release process is a reconnection site where the associated current sheet has the general geometry given by Fig. 2. An important parameter in our study is the value of the longitudinal reconnected magnetic field component.We must emphasize that recently, Efthymiopoulos et al. (2005) examined the particle dynamics in a 3-D RCS and found regular and chaotic behavior for particle orbits, depending on the value of the longitudinal magnetic field in a Harris type configuration. We distinguish here, three cases for the $B_{||}$ component: (1) the component is zero, (2) the component is large, and (3) the component has intermediate value. The case (1) was studied by Speicer (1965) and the case (2) was explored by Litvinenko (1996).

We can calculate the corresponding electric field seen by the particles in each elementary RCS by equating the flux of the magnetic energy into the sheet to the energy gained by the accelerated particles per unit time. Following this assumption we find that the electric field is given by the relation:

$$E = \frac{B_o^2}{4\pi e(<\Delta l>_e n_e + <\Delta l>_p n_p)} \tag{4}$$

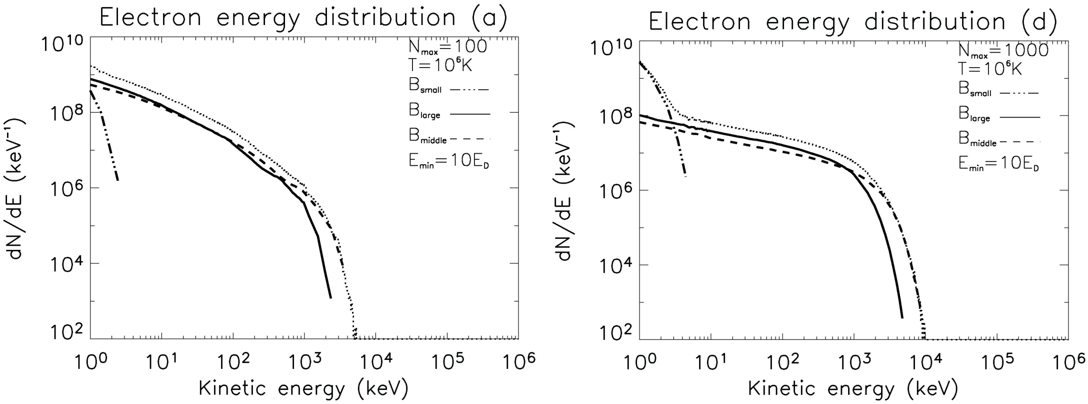

FIGURE 3. The resulting energy distribution of electrons for maximum number of interactions $N = 100$ and $N = 1000$. The normalized electric filed is $E_{min} = 10 \times E_D$. In each panel, the dashed dotted line corresponds to the case B_{small}, the dashed line corresponds to the case B_{middle}, the black line corresponds to the case B_{large} and the dotted line corresponds to the sum of these three distributions.

where $< \Delta l >_{\{e,p\}}$ is the average length of the RCS over which the particles are accelerated and $n_{\{e,p\}}$ is the particle density.

As it was state earlier, we assume that the energy release time series, produced by the CA model through the Eq. 3, is closely associated with the presence of a number of RCS in our system. This assumption is based on the fact that the energy release is produced by magnetic reconnection processes, simulated in the CA model by its redistribution rules. As the released energy calculated by the CA model is $\varepsilon(t) \sim B^2{}_o(t)$ (i.e. Eq. 3), we can construct a virtual electric field time series ($E(t)$) from the energy release time series using Eq. 4 for the electric field. Finally we can normalized this electric field time series to the Dreicer electric field value E_D ($= 5.5 \times 10^{-4}$ V/cm for the parameters used in our study).

Each injected particle enters into the acceleration volume and interacts successively with randomly selected, from the interval [1, N], elements of the electric field time series by performing a free flight between each interaction. At each particle - RCS interaction, the kinetic energy change is given by the relation:

$$\Delta E \; = \pm \; Ze\, E(t)\, \Delta l \tag{5}$$

where the plus (minus) sign corresponds to in (out of) phase interaction, Ze is the charge, $E(t)$ is the selected element of the virtual electric field time series given by the CA model and $\Delta l = \alpha < \Delta l >_{\{e,p\}}$. The parameter α is selected randomly to vary between zero and one at each particle - RCS interaction and plays the role of the acceleration coefficient, controlling the efficiency of the process.

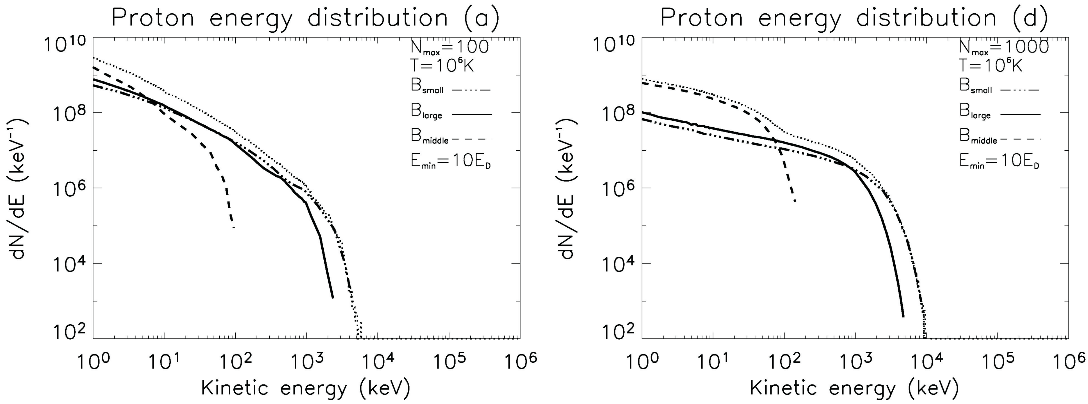

FIGURE 4. Same as Fig. 3 but for the case of protons.

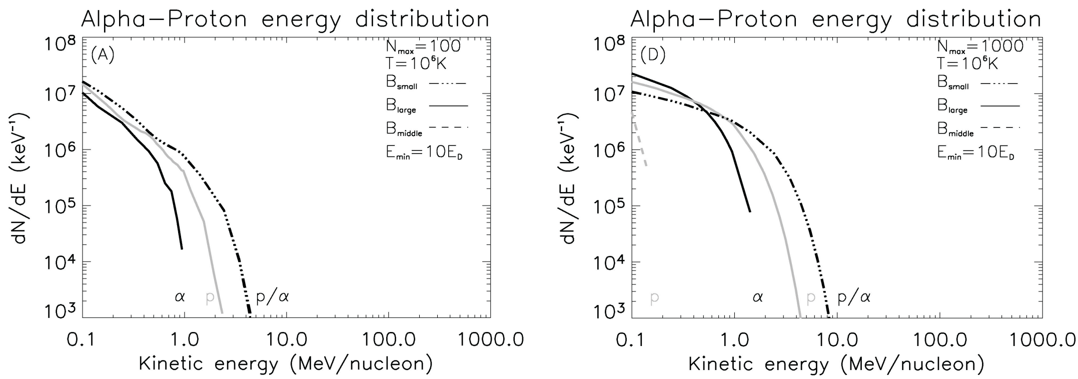

FIGURE 5. Same as Fig. 3 but for the case of alpha particles.

RESULTS AND DISCUSSION

In this section our preliminary results are presented (for a complete report see Dauphin et al. (2006)), for the case of electrons, protons and alpha particles, interacting with N RCS. Each particle population is injected into the acceleration volume with an initial thermal distribution of $T = 10^6$ K. We can perform a parametric study with respect to the number of interacting RCS (N), to the value of the longitudinal reconnecting magnetic field ($B_{\parallel}$) and to the normalization of the electric field with respect to the Dreicer value (E_{min}/E_D). In Figs. 3, 4, 5, we present the resulting particle (electrons, protons and alpha particles) distributions, for the case of $N = 100$ and $N = 1000$ with normalized electric field $E_{min} = 10 \times E_D$.

In addition to the acceleration process we can compute the resulting radiation flux of the accelerated particle distributions. In order to do so we choose to consider as a first

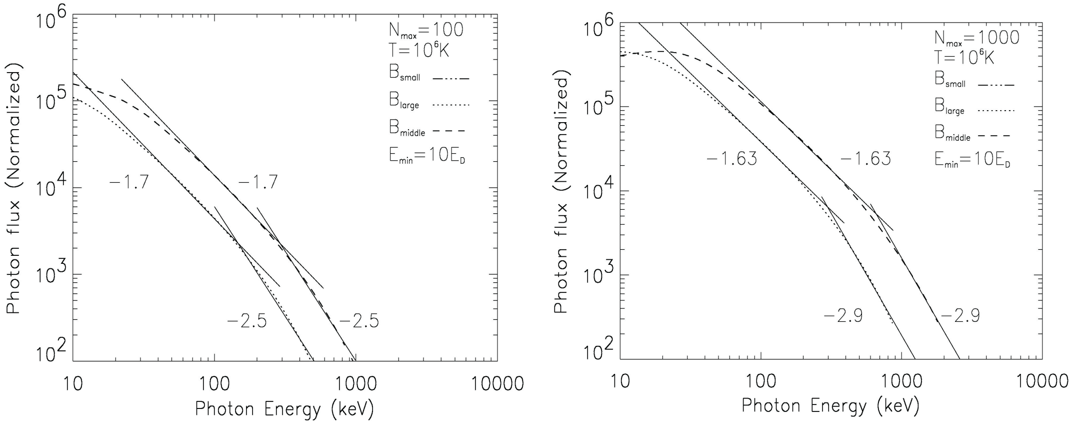

FIGURE 6. The emitted X-ray radiation calculated by the thick target approach for the case of electron distributions presented in Fig. 3.

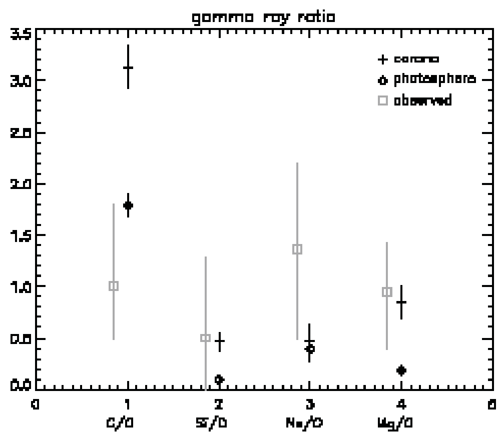

FIGURE 7. Ratio of the direct gamma ray lines calculated in the thick target approach from the proton and alpha energy distributions.The squares are deduced from the observations of Share and Murphy (1995), the crosses correspond to solar corona environment and the diamonds to photosphere.

approach, that energetic particles produce thick target radiation (for details see Brown 1971; Vilmer et al 1982). In other words, we assume that the accelerated particles after their escape from the acceleration volume are injected in a dense medium where they radiate all their energy instantaneously with no modification due to transport.

In Fig. 6 the emitted X-ray radiation of the electrons distributions presented in Fig. 3 is shown. The fitting was done by a power law in the energy ranges 10 -100 keV (considered as the low energy part) and 100 - 1000 keV (considered as the high energy part).

Finally, in Fig. 7 the ratio of the direct gamma ray lines calculated for the thick target approach from the proton and alpha particle energy distributions, for different realizations of our model parameters, are presented. The read marks in Fig. 7 corresponds to the observations reported by Share & Murphy (1995).

Summarizing, in this work we consider a global model for the acceleration and radiation process of particles (electrons, protons and alpha particles) in the complex evolving active regions (for details see Dauphin et al. 2006). Considering that the evolution of active regions can be simulated by the evolution of a Cellular Automaton (CA) model based on Self - Organized Criticality (SOC), we tried to connect the energy release process occurring in solar flares with the acceleration and radiation processes of energetic particles. We presented preliminary results for the accelerated particle distributions in respect to our model parameters (i.e. the number of reconnecting current sheets N, the value of the longitudinal reconnecting magnetic field $B_{\parallel}$ and the normalization of the electric field with respect to the Dreicer value E_{min}/E_D). Finally we considered the emitted radiation of the accelerated particle distributions, assuming the thick target approximation. More work is clearly needed in the future if we want to incorporate the transport of the particles and to include the radiation losses due to collisions inside the acceleration volume (i.e. use of the thin target emission) and to compere our numerical results with the existing observations.

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