ENERGETIC PARTICLE ACCELERATION AND RADIATION IN EVOLVING COMPLEX ACTIVE REGIONS*

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ABSTRACT

We present a model for the acceleration and radiation of solar energetic particles (electrons) in an evolving active region. The spatio - temporal evolution of the active region is calculated using a Cellular Automaton (CA) model for the energy release process. The acceleration of electrons is due to the presence of randomly placed, localized electric fields. We calculate the resulting kinetic energy distributions of the particles and their emitted X-ray radiation spectra, using the thick target approximation, by performing a parametric study with respect to number of electric fields present and the thermal temperature of the initially injected distribution.

1. INTRODUCTION

During the last two decades, due to the existence of several space-born solar instruments together with a number of ground based solar telescopes, a number of statistical studies of the solar flaring activity has been performed (for review see Vilmer 1993; Vilmer & Mackinnon 2003). These studies established that the frequency distributions of impulsive events (e.g. solar flares, X-ray bright points) 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 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.

The theoretical work for studying the evolution and the dynamics of complex active regions followed, in general, two different approaches:

(1). MHD numerical simulations (e.g. Galsgaard & Nordlund 1996; Einaudi et al. 1996; Georgoulis et al. 1998). According to these models, random shearing motions of the magnetic field lines at the photospheric boundary lead to the formation of current sheets inside the active region, where magnetic reconnection occurs. The MHD approach gives detailed insight into the smallscale processes (i.e. magnetic reconnection) in active regions, but has difficulty modelling the complexity of entire active regions and solar flares.

(2). 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; Vlahos et al. 2002). In these models the continuous loading of the active regions with new magnetic flux can produce several magnetic discontinuities. Simple rules were applied for the redistribution of

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magnetic fields and the release of magnetic energy at these discontinuities. The CA models can rapidly and efficiently treat the complexity of spatially extended, large systems but they face problems describing in details the small scale processes occurring.

Recently several efforts have been done to connect the two complementary approaches (the MHD simulations and the CA models). 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 most common approach for the particle acceleration models proposed for solar flares (for review on acceleration models see Anastasiadis 2002) is the decoupling of the different processes (i.e. the energy release, the acceleration, the transport and radiation). It is clear that in any effort to develop global models for solar flares, one must consider the coupling between different processes, from energy release process to particle acceleration, transport and radiation. This is not an easy task as these processes have different time and spatial scales and usually are acting simultaneously.

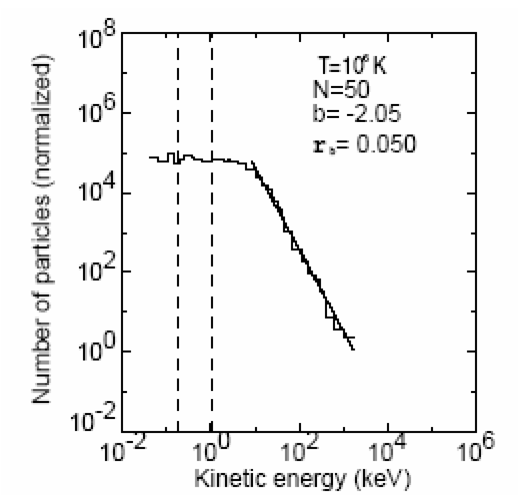

Figure 1. The average kinetic energy distribution of electrons accelerated for the case of N = 50 *and T*1 = 106 *K. The fit is given by Eq. 7 and the vertical dashed lines indicate the injected kinetic energy range.*

The main goal of this work, is to connect the energy release process during solar flares, through a cellular automaton model, with the particle acceleration and radiation processes and to compare our results with the observations. In the next section we outline the basic rules of the CA model, used for the calculation of the energy release time series. In Section 3, the acceleration model is presented, followed by the computed energy distribution of electrons and the corresponding X-ray radiation flux. Finally we discuss the possible extensions of this work.

2. THE CA MODEL FOR ENERGY RELEASE

For the study of the energy release process we use a 3- D Cellular Automaton (CA) model based on the Self - Organized Criticality (SOC). For a detailed description of the CA model see Vlahos et al. (1995) 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:

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

(4) The energy release is calculated using:

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

where B_i is the value of the magnetic field of given grid point i, which is becoming unstable when B_i $\geq$¸ B_{cr}, with B_{cr} been a critical value of the magnetic field.
An energy release time series ($\in^{2}(t)$) can be constructed, using Eq. 3. This time series obeys a double power-law frequency distribution and also exhibits a scale-invariant behavior and encloses a self - similar nature.

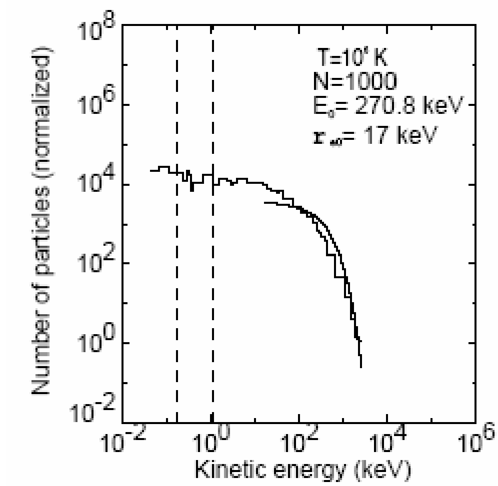

Figure 2. Same as Fig. 1, but for N = 1000. The fit is given by Eq. 8.

3. DESCRIPTION OF THE MODEL

In order to estimate the electric field strength in each RCS, we follow the calculation of Litvinenko (1996), using the Amp`ere law, with the assumption that a particle flow towards the RCS is produced by the electric drift. The electric field in given by the equation:

$$E = \frac{B^2}{4\pi en\Delta l} \tag{4}$$

where Δl is the maximum length over which the particles are accelerated and the ambient plasma has a density of $n = 10^{10}$ cm^{-3}. As the released energy calculated by the CA model is $\in^{2}(t) \sim B^2(t)$ (i.e. Eq. 3), we can produce a virtual electric field time series ($E(t)$) from the energy release time series using Eq. 4 for the electric field. Each injected electron enters into the acceleration volume and interacts

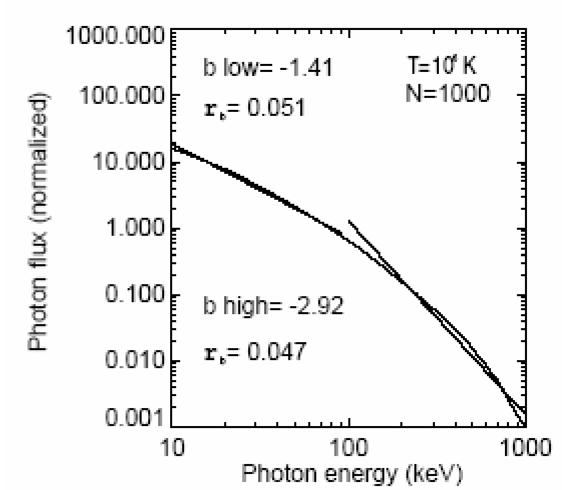

Figure 3. The calculated X-ray radiation spectrum of the resulting electron distribution given in Fig. 2. The fitting was performed in two energy ranges 10-100 keV and 100- 1000 keV and is given by power-laws.

successively with N randomly selected elements of the electric field time series. At each electron-RCS interaction, the kinetic energy change of an electron is given by the relation:

$$\Delta E_k = \pm \alpha e E(t) \Delta l \tag{5}$$

where the plus (minus) sign corresponds to in (out of) phase interaction, e is the electron charge and $\Delta l = 10^3$ cm. The parameter α is selected randomly to vary between zero and one at each electron - RCS interaction. A more detailed description of the acceleration model can be found in Anastasiadis et al. (1997). Our aim is to calculate the final kinetic energy distribution of the electrons, by performing a parametric study according to N, and to compute the resulting X-ray radiation flux using the thick target approximation.

4. RESULTS

According to our model, each electron performs a free flight between RCS of variable strength. We follow the interaction of a Maxwellian type velocity distribution of electrons, given by the form:

$$f(\upsilon) = \frac{n}{(2\pi)^{1/2} V_e} exp\left(-\frac{\upsilon^2}{2V_e^2}\right) \tag{6}$$

We inject electrons with initial velocity in the range $2 \leq (\upsilon/V_e) \leq 5$, where V_e is the thermal velocity and n is the ambient plasma density. We consider two different temperatures: $T_1 = 10^6$ K corresponding to $V_{e1} = 3.88 \times 10^8$ cm s^{-1} and $T_2 = 10^7$ K corresponding to $V_{e2} = 1.23 \times 10^9$ cm s^{-1}. The resulting thermal kinetic energies are 43 eV and 430 eV, respectively.

We are interested in calculating the average resulting electron distributions, in order to eliminate any effects of the random numbers, by performing a parametric study with respect to the maximum number N. Note that this parameter can be considered as a rough measure of the maximum trapping time of the injected electron distribution.

In Fig. 1 and 2 we present the numerically evaluated kinetic energy distribution (average of 10 sample runs) for $N = 50$ and $N = 1000$ respectively for the case of $T_1 = 10^6$ K. All of our resulting average kinetic energy distributions can be fitted for kinetic energies above 10 keV, either with a power law function of the form:

$$F(E_k) \approx E_k^{-b} \tag{7}$$

or with an exponential function of the form:

$$F(E_k) \approx exp\left(-\frac{E_k}{E_0}\right) \tag{8}$$

Our results suggest that, as the maximum number of interactions (*N*) increases, it affects the shape of the energy distribution, which begins to diverge from a well defined power law and an exponential tail is starting to develop. In addition to the acceleration process we compute the resulting X-ray radiation flux. In order to do so we choose to consider as a first approach, that energetic electrons produce thick target radiation (for details see Brown 1971). In Fig 3 the X-ray spectrum produced by the electron distribution of Fig 2 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). In Fig. 4 we present in a form of scatter plots our results for the power law index of the calculated X-ray spectra in respect to the maximum number *N* for the two temperatures used. For the low energy range (10 - 100 keV) the mean value of the index is -1.45 for $T_1 = 10^6$ K and -1.47 for $T_2 = 10^7$ K, as for the high energy part (100 - 1000 keV) the mean values are -2.96 and -3.08 respectively.

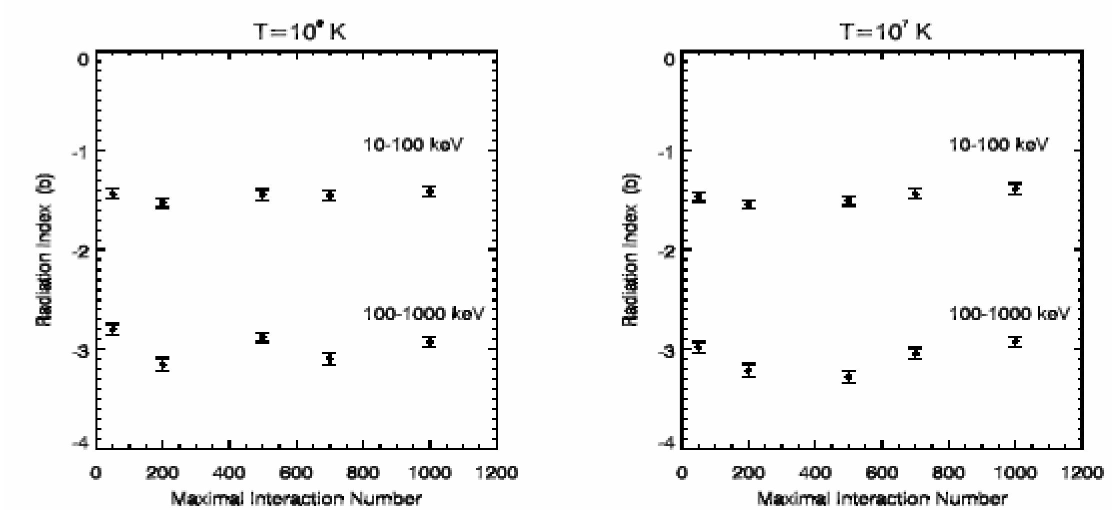

Figure 4. Scatter plots summarizing our results concerning the power law index of the emitted X-ray radiation in respect to the maximum number N for the two temperatures used.

5. SUMMARY AND DISCUSSION

In this work, the connection of the energy release process with the acceleration environment is attempted. Using a CA model, the turbulent driver of the convection zone (i.e. the random on going loading of the CA) is connected with the energy distribution of the accelerated particles. Our results for the kinetic energy distributions of electrons show a power-law or an exponential behavior depending upon their maximum number of interactions *N*. In addition, the X-ray radiation flux, using the computed kinetic energy distributions, was presented. The predicted spectra could be consistent with some observations (at least for the higher part of the predicted spectrum where Coulomb energy losses play a less significant role). The hardness of the predicted spectrum above 100 keV may be consistent with what is observed but a consistent photon flux should also be produced.

More work is clearly needed in the future if we want to incorporate the transport of the particles and to include 4 the radiation losses due to collisions inside the acceleration volume (i.e. use of the thin target emission). This approach can be done if we considered the newly develop CA model -named extended CA- (X-CA) (Isliker et al. 2001), taking advantage the consistent calculation of the magnetic and electric fields in the simulation box. In this direction, studies for the case a random walk process in a environment which has fractal properties, like the one produced by the CA models are currently under way (see Isliker & Vlahos 2003). We believe that much effort should be put in developing global models for the study of the solar corona, that can couple the different processes, occurring in different time and spacial scales. This approach will open a new highly promising and challenging field for solar physics research.

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