ACCELERATION AND RADIATION MODEL OF SOLAR ENERGETIC PARTICLES IN AN EVOLVING ACTIVE REGION

A. Anastasiadis[1], C. Gontikakis[2], N. Vilmer[3], and L. Vlahos[4]

[1]National Observatory of Athens, Institute for Space Applications and Remote Sensing, 152 36 Penteli, GREECE
[2] Research Center for Astronomy and Applied Mathematics, Academy of Athens, GREECE
[3]LESIA, Observatoire de Paris-Meudon, 92195 Meudon Cedex, FRANCE
[4] Department of Physics, University of Thessaloniki, 54124 Thessaloniki, GREECE

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 particles is due to the presence of randomly placed, localized electric fields. We calculate the resulting kinetic energy distributions of the particles by performing a parametric study with respect to the trapping time of the injected distribution. Our results show a power law or a power law with an exponential tail behavior for the resulting kinetic energy distribution, depending on the maximum trapping time of the injected particles in the acceleration volume. Finally we calculate the emitted radiation spectrum from the resulting energy distributions.

Key words: Sun, Flares: particle acceleration, radiation; Cellular Automata; Self Organized Criticality.

1. INTRODUCTION

The magnetic field of the Sun is the main driver of its flaring activity. Solar flares are the manifestation of an energy release process. During solar flares, magnetic energy of 10^{28} to 10^{34} ergs is released in the solar chromosphere and corona over a few minutes, by means of magnetic reconnection processes. It is believed that the energy release process during solar flares, gives rise to plasma heating, bulk mass motions and the acceleration of particles (electrons and ions). For a recent review on the acceleration of solar energetic particles see Anastasiadis (2002), and references therein.

A number of observations of flare radio emission (Benz 1985; Benz & Aschwanden 1992; Vilmer 1993; Aschwanden et al. 1995; Vilmer & Trottet 1997) indicates that the energy released during solar flares is fragmented. Following the above observational evidence, several qualitative models have been developed (for reviews see van den Oord 1994; Vlahos 1996; Bastian & Vlahos 1997). These models revealed the necessity to study and understand the global behavior of the evolution of the complex active regions. Two approaches are used to model the dynamic evolution of solar flares:

(1). MHD simulations (e.g. Galsgaard & Nordlund 1996; Einaudi et al. 1996; Dmitruk & Gomez 1998; 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 small-scale processes in active regions, but has difficulty modelling the complexity of entire active regions and solar flares.

(2). Cellular Automata (CA) models (e.g. Lu & Hamilton 1991; Lu et al. 1993; Vlahos et al. 1995; Georgoulis & Vlahos 1996; 1998). These models have shown that the energy release inside active regions may well be a result of an internal self-organization process. The continuous loading of the active region with new magnetic flux can produce several magnetic discontinuities. Simple rules were applied for the redistribution of 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.

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 2, 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.

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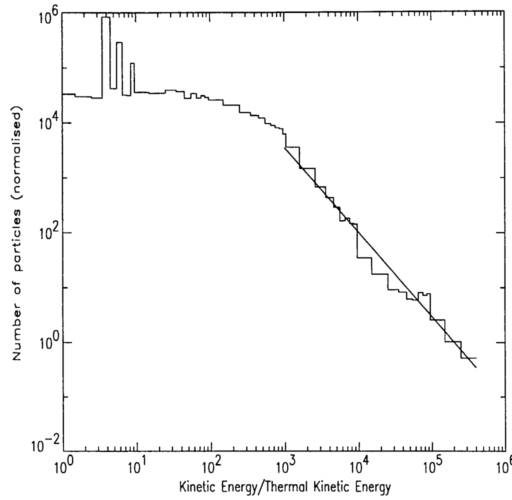

Figure 1. The average kinetic energy distribution of electrons accelerated after N=500 interactions. The electric field is calculated using Eq. 5 (Case I). The fit is given by Eq. 10 with $b = 1.53$

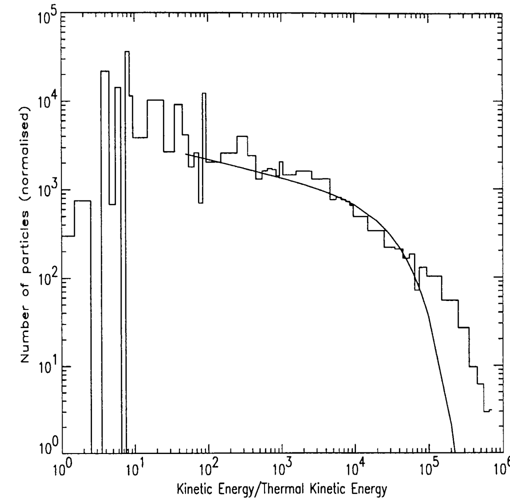

Figure 2. Same as Figure 1, but for $N = 2 \times 10^4$. *The fit is given by Eq. 11 with* $b = 0.24$ *and* $E_c = 4.5 \times 10^4$.

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; 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:

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

where B_i is the value of the magnetic field of given grid point i, which is becoming unstable when $B_i \geq B_c r$, with $B_c r$ been a critical value of the magnetic field.

An energy release time series ($\epsilon(t)$) 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.

3. DESCRIPTION OF THE MODEL

We use the following two different ways in order to estimate the electric field inside each RCS:

- **Case I**. If we assume that the flow velocity of the plasma inside the flaring region is of the order of the Alfvèn speed, v_A, then the electric field in the RCS can be considered as the convective field (see Anastasiadis et al. 1997):

$$E = | - \frac{\vec{v_A} \times \vec{B}}{c} | \approx \frac{B^2}{c(4 \pi n m_i)^{1/2}} \tag{4}$$

or

$$E(t) \approx 2.184\ 10^3\ B^2(t)\ n^{-1/2} \tag{5}$$

- **Case II**. Alternatively, if we follow the calculation of Litvinenko (1996), using the Ampère law, with the assumption that a particle flow towards the RCS is produced by the electric drift, we have:

$$E = \frac{B^2}{4 \pi\, e\, n\, \Delta l} \tag{6}$$

or

$$E(t) = \frac{B(t)^2}{4 \pi\, e\, n\, \Delta l} \tag{7}$$

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 $\epsilon(t) \sim B^2(t)$ (i.e. Eq. 3), we can produce a virtual electric field time series ($E(t)$) from the energy release time series using either Eq. 5 or Eq. 7 for the electric field. Each injected electron enters into the acceleration volume and interacts 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:

$$\Delta E_k = \pm\, \alpha\ e\, E(t)\, \Delta l \tag{8}$$

where the plus (minus) sign corresponds to in (out of) phase interaction, e is the electron charge and $\Delta l = 10^3$

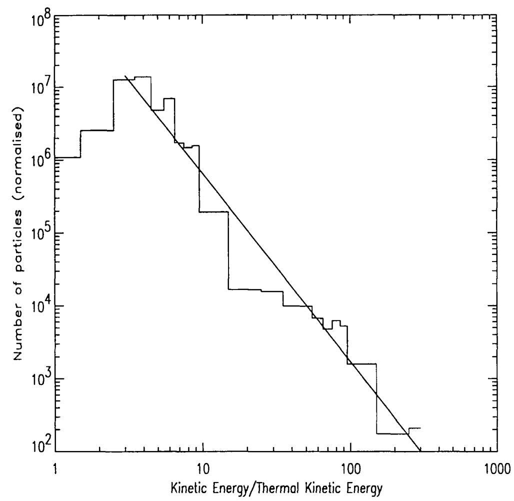

Figure 3. Same as Figure 1, but the electric field is calculated using Eq. 7 (Case II). The index is $b = 2.57$

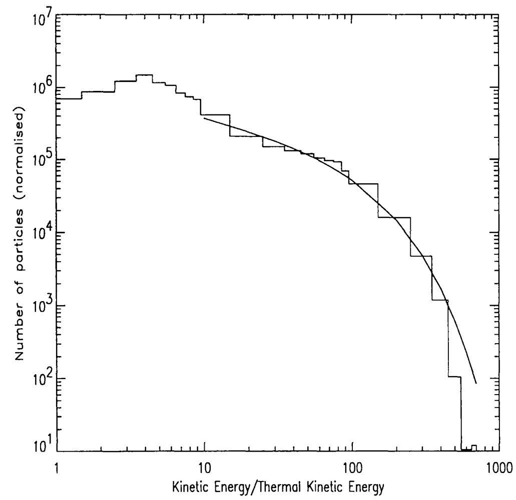

Figure 4. Same as Figure 3, but for $N = 2 \times 10^4$. *The fitting values are* $b = 0.5$ *and* $E_c = 110$.

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 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 evolution of a Maxwellian type velocity distribution of

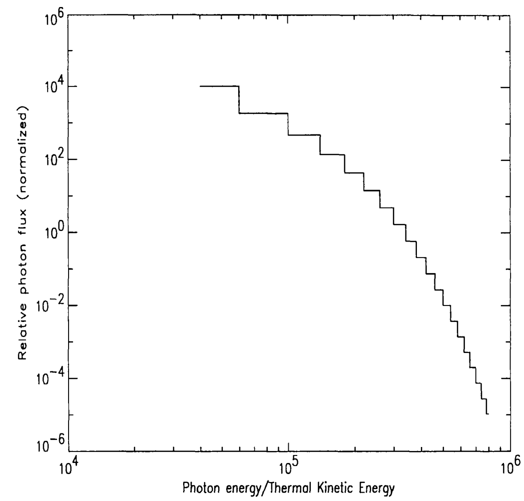

Figure 5. X-ray spectrum produced by the electron distribution of Figure 2

electrons, given by the form:

$$f(v) = \frac{n}{(2\pi)^{1/2} V_e}\, exp\left(-\frac{v^2}{2V_e^2} \right) \tag{9}$$

We inject electrons with initial velocity in the range $2 \leq (v/V_e) \leq 5$, where $V_e = 1.23 \times 10^9$ cm s^{-1} is the thermal velocity, resulting to a thermal kinetic energy of 430 eV.

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 of RCS (i.e. N). Note that this parameter is a rough measure of the maximum trapping time of the injected electron distribution.

In Figures 1 and 2 we present the numerically evaluated kinetic energy distribution (average of 10 sample runs) for $N = 500$ and $N = 2 \times 10^4$ respectively for the Case I of electric field estimation (i.e. using Eq. 5). Similarly in Figures 3 and 4 the results for the Case II (i.e. using Eq. 7) are presented.

For both Cases (I&II), and for $N = 500$ the resulting distribution is of a power law function of the form:

$$N(E_k) = a\, E_k^{-b} \tag{10}$$

On the other hand for $N = 2 \times 10^4$ we fitted the distribution with a combination of a power law and an exponential function of the form:

$$N(E_k) = a\, E_k^{-b} e^{-\frac{E_k}{E_c}} \tag{11}$$

Our preliminary results suggest that, as the trapping time of the electrons (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. Finally using the thick target approximation

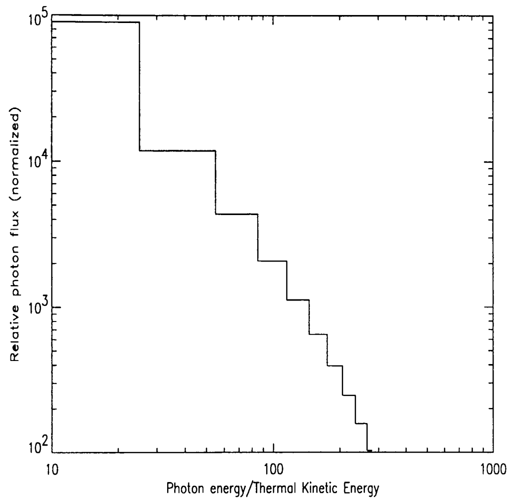

Figure 6. Same as Figure 5, but for the electron distribution of Figure 4

for the radiation of electrons we can calculate the corresponding X-ray radiation fluxes in respect to the parameter N. In Figures 5 and 6 the X-ray spectra produced by the electron distribution after $N = 2 \times 10^4$ for the Case I and II are shown respectively.

5. CONCLUDING REMARKS AND DISCUSSION

We believe that the way and the amount of the energy release process during solar flares, are very important parameters for any acceleration model, as they set up the environment for the acceleration and transport of solar energetic particles. 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 preliminary results for the kinetic energy distributions of electrons show a power-law or an exponential behavior depending upon their maximum trapping time N in the acceleration volume. In addition, preliminary results of the resulting X-ray radiation flux, using the computed kinetic energy distributions, were presented. In the near future we plan to compare the estimated radiation spectra with the observed ones. Furthermore, as we have introduced, recently, a new CA model - named *extended CA*- (X-CA) (Isliker et al. 2001), in which all the previous detected MHD -inconsistencies (see Isliker et al 1998; 2000) were removed, we plan to apply the presented approach for the acceleration and radiation of particles in such an environment.

We believe that a new and highly promising field of research, which differs from the localized acceleration approach of solar energetic particles, is now emerging.

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