PARTICLE ACCELERATION AND RADIATION IN AN EVOLVING ACTIVE REGION BASED ON A CELLULAR AUTOMATON (CA) MODEL

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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 particles is due to the presence of randomly placed, localized electric fields. We calculate the resulting kinetic energy distributions of the particles and the emitted radiation by performing a parametric study with respect to the trapping time of the injected distribution.

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

1. INTRODUCTION

During the last decade, it has been widely acknowledged that the way, as well as the amount, of the energy released during solar flares, play an important role to the acceleration, transport and radiation processes of solar energetic particles (for recent review 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 the fragmentation of the released energy during solar flares. Following the above observational evidence, 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). These models revealed the necessity to study and understand the global behavior of the evolution of the complex active regions. Two approaches are used:

(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. 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. In Section 4, we compute the energy distribution of electrons as well as 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; 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:

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

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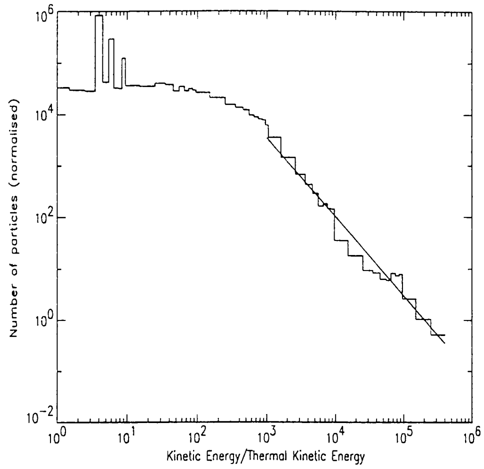

Figure 1. The average kinetic energy distribution of electrons accelerated after N=500 interactions. The electric field is calculated using Eq. 4 (Case I). The fit is given by Eq. 8 with $b = 1.53$

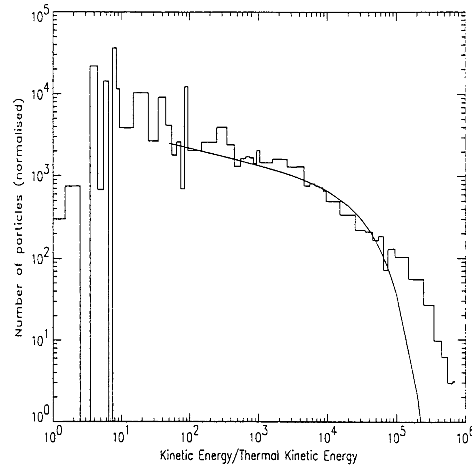

Figure 2. Same as Figure 1, but for $N = 2 \times 10^4$*. The fit is given by Eq. 9 with* $b = 0.24$ *and* $E_c = 4.5 \times 10^4$*.*

(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 $B_i \geq B_{cr}$, with B_{cr} 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):

$$E = \left| -\frac{\vec{v_A} \times \vec{B}}{c} \right| \approx 2.184\, 10^3\, B^2(t)\, n^{-1/2} \tag{4}$$

- **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:

$$E = \frac{B(t)^2}{4 \pi\, e\, n\, \Delta l} \tag{5}$$

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. 4 or Eq. 5 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:

$$\Delta E_k = \pm\, \alpha\, e\, E(t)\, \Delta l \tag{6}$$

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 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

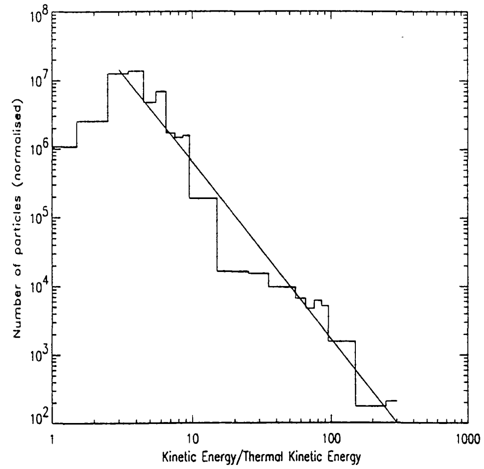

Figure 3. Same as Figure 1, but the electric field is calculated using Eq. 5 (Case II). The index is $b = 2.57$

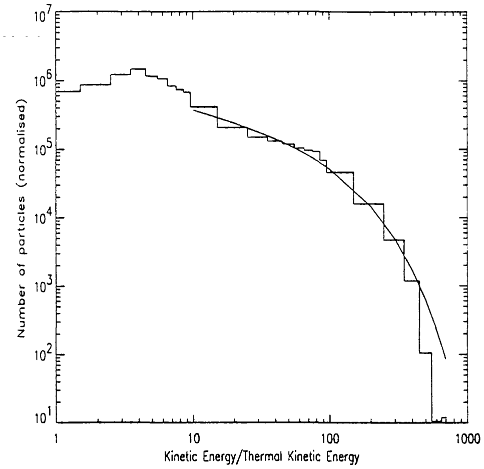

Figure 4. Same as Figure 3, but for $N = 2 \times 10^4$. *The fitting values are* $b = 0.5$ *and* $E_c = 110$.

evolution of a Maxwellian type velocity distribution of electrons, given by the form:

$$f(v) = \frac{n}{(2\pi)^{1/2} V_e} \, exp\left(-\frac{v^2}{2V_e^2} \right) \qquad (7)$$

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. 4). Similarly in Figures 3 and 4 the results for the Case II (i.e. using Eq. 5) are presented.

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

$$N(E_k) = a\, E_k^{-b} \qquad (8)$$

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:

$$N(E_k) = a\, E_k^{-b} e^{-\frac{E_k}{E_c}} \qquad (9)$$

Finally, we compute the X-ray emission radiated by the accelerated particles using the thick target approximation (Brown, 1971; Vilmer et al., 1982). We assume that the electrons, after their escape from the acceleration volume, are reaching a high density medium where they radiate their energy.

If we consider an electron of initial energy E_0, the produced number of photons of energy $h\nu$ is given by:

$$\mu(h\nu, E) = \int_{E_0}^{h\nu} \sigma(h\nu, E)\, n_p\, v(E)\, \frac{dE}{dt}\, dt \qquad (10)$$

where $\sigma(h\nu, E)$ is the cross-section coefficient of the bremstruhlung emission, n_p is the density of the ambient plasma, $v(E)$ is the velocity of the particle and $\frac{dE}{dt}$ is the energy loss due to collisions. Then, the emitted flux of an initial energy distribution of electrons $F(E_0)$, in the range E_0, $E_0 + dE$, is given by the relation:

$$I(h\nu) = \int_{h\nu}^{+\infty} F(E_0)\, \mu(h\nu, E_0) dE_0 \qquad (11)$$

In Figures 5 and 6 the calculated X-ray spectra produced by the electron energy distribution after $N = 2 \times 10^4$ interactions for the Case I and II, using Eq. 11, are shown respectively.

5. 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 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. In addition, preliminary results of the X-ray flux resulting from the electron distributions of Fig.2 and Fig.

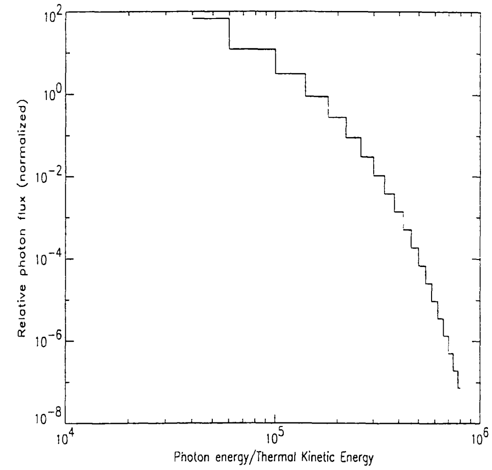

Figure 5. X-ray spectrum produced by the electron distribution of Figure 2

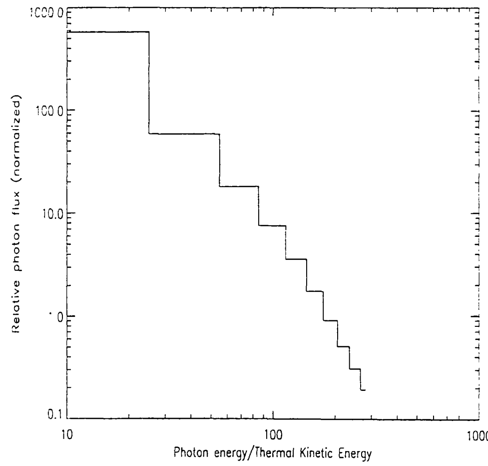

Figure 6. Same as Figure 5, but for the electron distribution of Figure 4

4 have been presented. More work is clearly needed in the future if to compare with observations. 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. Finally, it will be quite interesting in a second step to incorporate in our model the case of protons.

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REFERENCES

Anastasiadis, A. 2002, J. Atmosph. Solar - Terrestr. Phys., 64(5-6), 481

Anastasiadis, A., Georgoulis, M. K., & Vlahos, L. 1997, ApJ, 489, 367

Aschwanden, M. J, Montello, M., Dennis, B. R., & Benz, A. O. 1995, ApJ, 440, 394

Bastian, T. S., & Vlahos, L. 1997, in Lecture Notes in Physics, Vol. 483, ed. G. Trottet, (Springer-Verlag), 68

Benz, A. O. 1985, Sol. Phys., 96, 357

Benz, A. O., & Aschwanden, M. J. 1992, in Lecture Notes in Physics, Vol. 399, ed. Z. Svestka et al., (Springer-Verlag), 106

Brown, J. C. 1971, Sol. Phys., 18, 489

Dmitruk, P., & Gomez, D. O. 1998, ApJ, 505, 974

Einaudi, G., Velli, M., Politano, H., & Pouquet, A. 1996, ApJ, 457, L13

Galsgaard, K., & Nordlund, A. 1996, J. Geophys. Res., 101, 13445

Georgoulis, M., & Vlahos, L. 1996, ApJ, 469, L135

Georgoulis, M., & Vlahos, L. 1998, A&A, 336, 721

Georgoulis, M., Velli, M., & Einaudi, G. 1998, ApJ, 497, 957

Isliker, H., Anastasiadis, A., & Vlahos, L. 2000, A&A, 361, 1134

Isliker, H., Anastasiadis, A., & Vlahos, L. 2001, A&A, 377, 1068

Isliker, H., Anastasiadis, A., Vassiliadis, D., & Vlahos, L. 1988, A&A, 335, 1085

Lu, E. T., & Hamilton, R. J. 1991, ApJ, 380, L89

Lu, E. T., Hamilton, R. J., McTierman, J. M., & Bromund, K. R. 1993, ApJ, 412, 841

Litvinenko, Y. E. 1996, ApJ, 462, 997

van den Oord, G. H. J., ed. 1994, Fragmented Energy Release in Sun and Stars (Kluwer)

Vilmer, N. 1993, Adv. Space Res., 13(9), 221

Vilmer, N., Kane, S. R, & Trottet, G., 1982, A&A 108, 306

Vilmer, N., & Trottet, G. 1997, in Lecture Notes in Physics, Vol. 483, ed. G. Trottet,(Springer-Verlag), 28

Vlahos, L. 1996, in Radio Emission from the Stars and the Sun, ASP Confer. Ser., 93, ed. A. R. Taylor and J. M. Paredes (ASP Press), 355

Vlahos, L., Georgoulis, M. K., Kluiving, R., & Paschos, P. 1995, A&A, 299, 897