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Electron Acceleration in Solar Flares by Spatially Random DC Electric Fields

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Abstract.
A global model for the acceleration of electrons in the framework of the *statistical flare* model is presented. In such a model, solar flares are the result of an internal Self-Organised Critical (SOC) process in a complex, evolving, and highly inhomogeneous active region. We have developed a 3D cellular automaton model that simulates flaring activity which extends over an active subflaring background. We derive the spatio-temporal evolution of the active region and the resulting energy release time series, which is associated with an electric field time series. We trace an injected electron distribution in this environment, assuming that the acceleration process is due to randomly placed, localised DC electric fields. Our numerical results regarding the kinetic energy distribution of the accelerated electrons show a power-law or an exponential behaviour, depending upon the maximum trapping time of the energetic particles inside the acceleration volume.© 1998 Elsevier Science Ltd. All rights reserved.

1 Introduction

Solar-terrestrial coupling has its origin in solar events. One kind of such events are solar flares, which have been associated with the occurrence of intense geomagnetic storms. In this context, comprehensive knowledge of solar flare dynamics is highly desirable.

Solar flares are the manifestations of an energy release process in solar active regions. During solar flares, magnetic energy of 10^{29} to 10^{33} ergs is released, by means of magnetic reconnection, in the solar chromosphere and corona over a few minutes. This released energy is separated in three parts: (1) intense localised heating, (2) particle acceleration and (3) mass flows (Priest, 1992).

A large number of observations on the spatio-temporal evolution of solar flares have been collected (for reviews see: Dennis, 1985; Ramaty and Murphy, 1987; Vilmer, 1987; Dennis, 1988; Pick et al., 1990) and their interpretation lead to a variety of proposals for acceleration processes such as MHD waves, shock waves, DC electric fields, double layers, coherent acceleration processes etc. (for reviews see: Heyvaerts, 1981; de Jager, 1986; Vlahos, 1989; Melrose, 1990; Miller et al., 1997).

Recent observations of flare radio emission (Kuijpers et al., 1981; Benz, 1985; Vilmer, 1993; Aschwanden et al., 1995) suggest that the energy released during solar flares is fragmented. This suggestion led to the development of a number of qualitative models for the energy release in solar flares (for reviews see: Vlahos, 1993; 1994; Bastian and Vlahos, 1997). These models revealed the necessity to study and understand the global behaviour of the evolution of active regions. Two approaches can be used for this purpose:

(1). MHD simulations (e.g. Galsgaard and Nordlund, 1996; Einaudi et al., 1996). According to these models, random shearing motions of the magnetic field lines at the photospheric boundary lead to the formation of a number of current sheets inside the active region, where magnetic reconnection occurs.

(2). Cellular Automata simulations. Lu and Hamilton (1991) and Lu et al. (1993) were the first to apply cellular automata simulations to solar flares. They showed that the energy released inside the active region may well be a result of an internal self-organisation process. The continuous loading of the active region with new magnetic flux produces several magnetic discontinuities. The energy released locally affects the entire structure of the flaring region by redistributing the magnetic field, creating new instabilities in an avalanche -like manner.

Several qualitative attempts to study the problem of particle acceleration in the framework of a concrete proposal for a fragmented energy release process have been made in the past (e.g. Holman, 1985; Haerendel, 1994). Anastasiadis and Vlahos (1991; 1994) proposed a model for the acceleration of particles (electrons and ions) by an ensemble of shock waves. In this model the energy

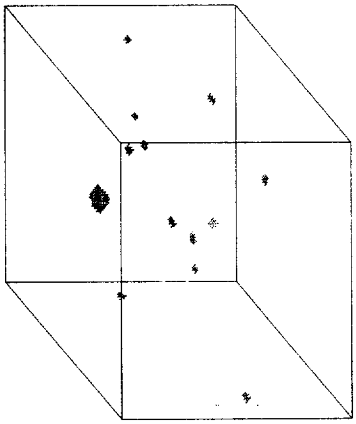

Fig. 1. Spatial configuration of the 3D simulation box, illustrating the clustering of unstable grid points.

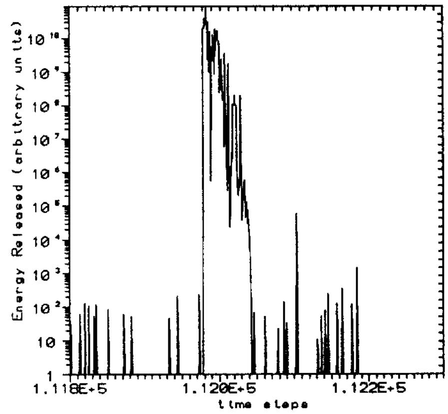

Fig. 2. The energy release time series corresponding to the configuration of Fig.1.

was assumed to be released by means of many localised, small - scale explosive phenomena which are the drivers of a number of shock fronts (small - scale, short - lived discontinuities).

In this paper we present a model for electron acceleration based on a random number of localised electric fields, which are closely associated with the energy released during solar flares. We are interested in the global characteristics of the energy release process and the acceleration of high energy electrons.

2 The statistical flare

In a series of recent articles, Vlahos et.al. (1995), Georgoulis et al. (1995) and Georgoulis and Vlahos (1996), have developed a cellular automaton model, based on the concept of Self-Organized Criticality (Bak et al., 1987; Tang and Bak, 1988). The main goal was to explore the origin of the frequency distribution of solar flares, the problem of coronal heating by nanoflares and the variability of the occurrence frequency of solar flares. In these articles "flares" are not considered as isolated localised explosions but rather as randomly appearing clusters of reconnection sites in a highly inhomogeneous topology. The active regions are continuously in a "flaring" state but the spatio-temporal evolution of the explosions changes randomly inside the active region. Vlahos et al. (1995) named this type of flaring activity "*statistical flare*".

The basic rules of the statistical flare model are:

1. A 3D cubic lattice represents an active region. To each grid point a random value of magnetic field is assigned (initial loading).

2. Randomly selected grid points gain increments δB, which are selected also randomly out of the following power-law probability distribution function (loading)

$$P(\delta B) \sim (\delta B)^{-5/3} \tag{1}$$

where $P(\delta B)$ is the probability of occurrence of a certain increment δB. Since the increments δB in eq. (1) are supposed to be the outcome of a highly turbulent process in the convection zone, the particular value of the exponent (i.e. that it is a multiple of 1/3) is loosely explained. It is clear, however, that the connection between eq. (1) and the turbulent convection zone should be analyzed further (see Galsgaard, 1996; Georgoulis and Vlahos, 1997).

3. The continuous loading generates local discontinuities which excite currents ($\vec{\nabla} \times \vec{B} \propto \vec{J}$). If a certain critical threshold B_{cr} is exceeded, the topology is considered unstable and is relaxed by redistributing magnetic field to the neighbourhood and by releasing energy (relaxation process).

The amount of the released energy during the restructuring of the magnetic field at a single grid point i is given by the relation (Georgoulis et al., 1995; Georgoulis and Vlahos, 1996)

$$\epsilon_{ri} \sim \left(B_i - \frac{6}{7}B_{cr}\right)^2 \tag{2}$$

where B_i is the local magnetic field at the ith grid point. This energy is treated as the magnetic energy release during magnetic reconnection.

By performing a number of iterations, we are able to obtain spatio-temporal information on the energy released (in arbitrary units). In Fig.1 we demonstrate the clustering of current sheets of all sizes for a small time interval. The corresponding energy release time series is given in Fig. 2 .

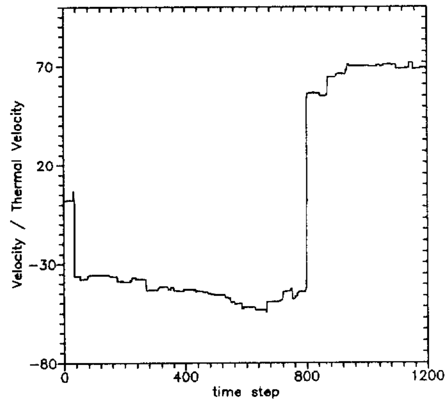

Fig. 3. The temporal evolution of the velocity of a single electron. The sign of the velocity corresponds to the direction of motion.

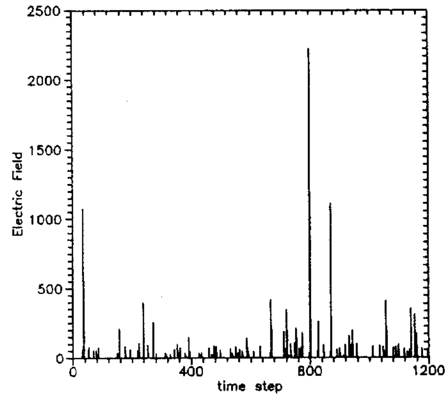

Fig. 4. The electric field time series which the electron, considered in Fig.1, experiences.

The energy release time series obeys a well-defined double power-law frequency distribution (see Fig.1 of Georgoulis and Vlahos, 1996), it exhibits a scale-invariant behaviour and it encloses a self-similar nature (Vlahos et al., 1995; Georgoulis et al., 1995). It turned out that, due to self-similarity, our results are not affected by the size of the simulation box, provided that the box is not too small (not smaller than $50 \times 50 \times 50$).

3 Model for electron acceleration

Our acceleration model is based on the interaction of electrons with a number of Reconnecting Current Sheets (RCS). We assume that the magnitude of the electric field inside each RCS is comparable to the convective electric field, due to the ambient plasma flow and the local magnetic field. If the flow velocity of the plasma inside the flaring region is of the order of the Alfvén speed v_A, then the convective electric field is given by the relation

$$E = | - \frac{\vec{v_A} \times \vec{B}}{c} | \approx \frac{B^2}{c(4\pi n m_i)^{1/2}} \quad (3)$$

where B is the magnetic field, c is the speed of light, n is the ambient plasma density and m_i is the proton mass. From the above relation we can find that the convective electric field in Volts cm^{-1} is

$$E(t) \approx 2.184\ 10^3\ B^2(t)\ n^{-1/2} \quad (4)$$

Litvinenko (1996) performed a similar calculation in order to find a relation between the magnetic field and the electric field in a RCS, using a self-consistent calculation for the collisionless case.

We consider now that the ambient plasma parameters inside our flaring region are: the density $n = 10^{10}$ cm^{-3}, the temperature $T = 10^7$ K, corresponding to an electron thermal velocity $V_e = 1.23 \times 10^9$ cm s^{-1} and a kinetic energy $E_T = 430$ eV.

The SOC model, which was described in the previous section, connects the magnetic field strength $B(t)$ at a given time t with the derived energy release time series $\epsilon_r(t)$, as $\epsilon_r(t) \sim B^2(t)$ (see eq. (2)). Thus we can construct a new time series $E(t)$ which represents the electric fields at each RCS, associated with the energy release sites, using the relation

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

This new time series exhibits the same characteristics as the energy release time series. These highly localised and strong electric fields will excite plasma instabilities. The particle, interacting with the electric field and the plasma waves, will depart from the RCS with a final energy gain or loss, which for our purpose will be simulated by a "virtual" electric field (see below).

Each electron of the ambient Maxwellian distribution

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

with initial velocity in the range $2 \leq (v/V_e) \leq 5$, remains inside the flaring region for a different number of time steps (N_j), selected randomly from an interval $(1, N_{max})$. The parameter N_{max} is the maximum number of time steps that the injected electron distribution remains inside the acceleration volume.

Each injected electron enters into the acceleration volume and interacts successively with $N_j \leq N_{max}$ randomly selected elements of the electric field time series.

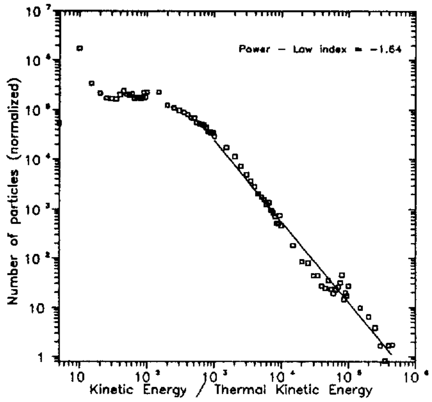

Fig. 5. The numerically evaluated kinetic energy distribution of accelerated electrons (average of 10 sample runs) for $N_{max} = 500$.

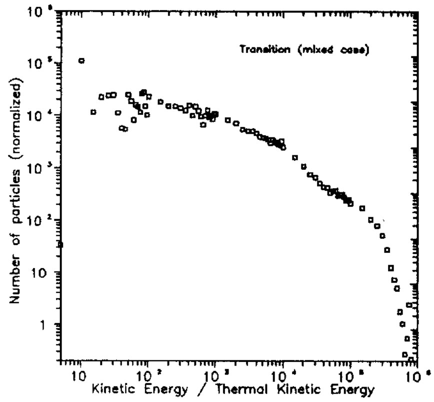

Fig. 6. The same as Fig. 5 but for $N_{max} = 10000$.

Following this approach, electrons with the same initial kinetic energy E_k are neither entering into the acceleration volume at the same time and at the same position, nor are they escaping from the same place at the same instant.

We include the case of energy losses for the electrons by assuming that their interaction with the associated electric field can be accomplished either in phase or out of phase. This selection is also random. We do not consider the effect of Coulomb collisions in our model as we are initialising the tail of the Maxwellian distribution and thus the collision frequency is small.

We define an "acceleration coefficient" α which is selected randomly to vary between zero and one at each electron - RCS interaction. With this coefficient, we intend to simulate the fact that only a portion of the energy released goes to the particle acceleration process; the rest of this energy heats the ambient medium of the flaring region. Thus an electron interacts with a portion of the electric field ("virtual field") allocated at a RCS. The variation of the "acceleration coefficient" at a single electron - RCS interaction, represents also the fact that each electron travels along the RCS' electric field a different distance, and thus the effective acceleration length Δl is not constant. In this way the variability of Δl can also be assigned to the coefficient α.

Under the above assumptions, the kinetic energy change of a single electron in eV, due to the interaction with an electric field $E(t)$, at a given time t, is given by the relation:

$$\Delta E_k = \pm \alpha \ e \ E(t) \ \Delta l_{max} \tag{7}$$

where the plus (minus) sign corresponds to in (out of) phase interaction, e is the electron charge ($e = -1$) and $\Delta l_{max} = 10^3$ cm is the maximum effective length of the current sheet where the electric filed $E(t)$ is located.

The only free parameter for our model is the maximum number of time steps (N_{max}) that the electron distribution, moving inside the flaring region, will complete before escaping from the box and thus the maximum number of RCS it can experience. A more detailed description of the model can be found in Anastasiadis et al. (1997).

4 Results

According to our model, an electron performs a "free flight" between electric fields of variable strength, which exhibit a power-law frequency distribution. The temporal evolution of the velocity (normalised to the thermal one) of a single electron is presented in Fig. 3 and the part of the electric field time series with which this particular particle interacts is shown in Fig. 4. Note that the sign of the velocity in Fig. 3 corresponds to the direction of motion. We believe that this process is not a normal diffusion (i.e. normal random walk, Brownian motion), as the electric field as well as the energy gain of a single particle exhibit large variations locally.

We are interested in the electron population given by eq. (6), with initial velocity range $2 \leq (v/V_e) \leq 5$. We normalise the injection distribution in such a way that $f(5V_e) = 1$ and follow numerically the kinetic energy change of 1000 electrons per injected velocity bin. The final kinetic energy distributions of the accelerated electrons (those with $E_k > E_T = 430$ eV) for the interval $(1, N_{max})$ are given in Fig. 5 - 7. These are averaged distributions over 10 sample runs with the same parameters.

The kinetic energy distributions for the high energy electrons (with $(E_k/E_T) > 10^3$) initially exhibit a well - defined power-law behaviour. The power-law index has a value of -1.64 initially (for $N_{max} = 500$) and as the maximum trapping time increases it becomes flatter, reaching -1.44 (for N_{max}= 5000). The relative error in the calculation of the above indices is less than 3 %. Further increase of the trapping time affects the shape of the final distribution, which begins to diverge from the power-law behaviour and an exponential tail is starting to develop. For N_{max}=10000, the shape of the distribution deviates significantly from either power-law or exponential behaviour. Finally, further increase of N_{max} leads to the emergence of an exponential law. The electron distribution in this stage becomes a "thermal" one with an "effective temperature" of the order $10^{5-6} \times E_T$. The energetic electrons, in this case, remain longer time intervals inside the acceleration volume and try to reach an equilibrium with the mean energy associated with the random electric fields.

The maximum energy reached by the electrons is of the order of several MeV. This value is connected with the selection of the maximum effective acceleration length Δl, which on the other hand does not influence the overall behaviour of the distributions. There is a close connection between the structure and the nature of the energy release $\epsilon_r(t)$ or the electric field $E(t)$ time series and the resulting energy distributions. This is obvious as, if we assume a random type time series (white noise) then our distributions do not exhibit any kind of structure (power-law or exponential type).

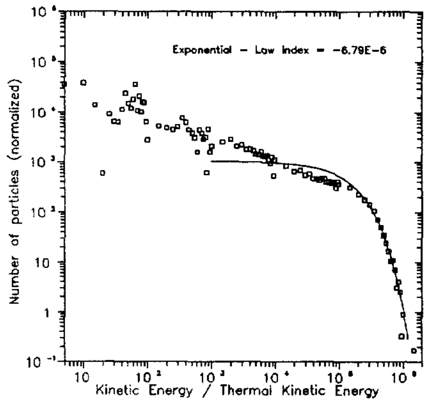

Fig. 7. The same as Fig. 5 but for $N_{max} = 40000$.

5 Summary

We propose, in this study, that electrons are accelerated by randomly placed DC electric fields inside an evolving active region. We use the statistical flare model in order to overcome the lack of understanding the way and the amount of the energy released in solar flares. Thus we simulate the spatio-temporal evolution of the energy released in active regions and subsequently we trace electrons inside this highly structured environment.

The injected electrons move inside this environment sensing either an electric field with varying strength locally or flying long distances without any interaction. This movement departs radically from the well known random walk with uniformly placed electric fields. The free parameter in this study is the maximum allowed number of interactions of each electron with the electric fields (N_{max}). Assuming that it takes a certain mean time for each electron - electric field interaction, then by increasing N_{max} we increase, on the average, the time that the injected distribution remains inside the energy release region (the trapping time). It is clear that N_{max} is only a rough measure of the trapping time.

Our main conclusions are:

1. There is a close connection between the turbulent driver inside the convection zone (power-law in the loading process), the frequency distribution of flares (power-law behaviour) and the energy distribution of accelerated particles.

2. The several types of solar flares, i.e., "nonthermal" (showing power-law behaviour), "thermal" (having an exponential distribution) or "hybrid", may be related to the the maximum trapping time of the energetic particles inside the active region. For short trapping time the distribution of energetic electrons exhibits a well - defined power-law behaviour. As the trapping time increases, the power-law distribution becomes flatter until an exponential tail is starting to develop (transition region). Further increase of the trapping time leads to exponential distribution for the energetic electrons.

It is obvious that the differences between our estimated energy distributions and the ones derived by the analysis of the observational data are due to the fact that no transport of the electrons is taken into account in this article. Many questions still remain open and will be addressed in a future study: (a) A more detailed connection of our study with the time evolution of the energy release process. (b) Including transport of energetic particles in our model.

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