SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

PARTICLE ACCELERATION IN SOLAR FLARE: LINKING BETWEEN THE MAGNETIC ENERGY RELEASE AND ACCELERATION PROCESS

C. Dauphin[1]

Abstract. Particle accelerated in solar flares draw their energy from the magnetic field. The dissipative scale of the magnetic energy in the solar corona implies that the magnetic energy is transmitted to the particles through a large number of dissipative regions (DR). Although not directly observed, the magnetic energy release process is assumed to evolve in a SOC state which leads to a power-law behaviour of the spectrum of the energy released in each DR. We present an approach to link the magnetic energy release to the acceleration process that occurs in each DR to finally compute the particle energy distribution. We consider that each accelerated particle leaves the acceleration region after one interaction but we introduce a distribution of the particle acceleration lengths inside each acceleration region. We finally compare our different results with particle energy distributions deduced from solar flare observations and we discuss the assumptions of the model.

1 Introduction

A solar flare is defined as a sudden transfer of magnetic enthalpy to the ambient coronal plasma leading to heating, flows and particle acceleration. Observations and analyses of hard X-ray emissions is the most direct diagnostic of these non thermal particles. The last decades of observations have shown that a large number of particles are accelerated ($\sim 10^{38}$ electrons.s^{-1}) to energies going up to several MeV, which implies high efficiency for the acceleration mechanism.

One of the most relevant informations that constrains the physical process that occurs during particle acceleration is certainly provided by the particle energy spectrum. Generally, hard X-ray spectra are reproduced by a double power law electrons spectrum. These double electrons power law spectra show a steep break generally between 10 keV and 100 keV. The spectral index below the break is usually lower than the spectral index at higher energy.

None of the existing acceleration mechanisms can explain the energetic particle distribution deduced from observations. In this paper, an attempt is made to explain these universal double power law electrons spectra. The basic idea is to link the particle acceleration process to the energy release process.

The energy of all aspects of flare process, including particle acceleration, must come ultimately from the release of the stored magnetic energy. The way to release the magnetic energy stored in the corona is the formation of small scales magnetic discontinuities where the frozen in law is violated and where instabilities and anomalous resistivity can easily rise. The value of the dissipative scale in the solar corona implies that the magnetic energy is dissipated and transmitted to the particles through a large number of dissipative regions. Thus, every model of particle acceleration during a solar flare has to take into account the large scale physical process that leads to the appearance of the small scales dissipative regions where the particle acceleration process takes place.

Several authors have already investigated the problem of particle acceleration by multiple acceleration regions by using either, a p-model (Decamp & Malara 2006), MHD simulations combined with a relativistic test particle code (Dmitruk et al. 2003, Onofri et al. 2006) or CA models in a self-organized criticality (SOC) state combined with acceleration in a reconnecting current sheet (Anastasiadis et al. 2004; Dauphin et al. 2006). These works are based on the same concept. Every particle interacts with a large number of acceleration regions. At each

[1] LESIA, CNRS and Observatoire de Paris-Meudon, 5 Place Janssen, F-92195 Meudon cedex, France

interaction, the energy gain of the particle is proportional to the electric field, which is function of the magnetic energy.

These different studies, which can be considered as stochastic particle acceleration models, failed to take into account the particle energy distribution resulting of the particle acceleration process inside each DR. The small scales are not accessible with the MHD simulations and there is no dependence of the energy gain as a function of the particle in work using a CA model. A large number of work have been devoted to analytical and numerical analysis of particle acceleration from a single acceleration site by direct electric field inside different magnetic geometries (e.g. Dalla et Browning 2006). These different studies usually found a power law particle energy distribution due to the configuration of the magnetic field that generates a chaotic behaviour of the particle trajectories.

To take into account this small-scale process with the magnetic energy release process, we present in this paper a model of particle acceleration in a "gaz" of acceleration regions. We consider that each accelerated particle leaves the acceleration region after one interaction but we introduce a distribution of the particle acceleration lengths inside each acceleration region.

2 Model

Details on the model are given in Dauphin (2006). We consider first an isolated acceleration region (AR). Particles are accelerated by the electric field into the AR and gain energy from the magnetic energy. Following Dauphin et al. (2006), we equate the magnetic energy flux to the particle energy flux in order to determine the electric field into the acceleration region:

$$E_{AR} = \alpha \frac{B_{free}^2}{4\pi e(< \Delta l_e >_{n_e} n_e + < \Delta l_p >_{n_p} n_p)} \tag{2.1}$$

where α, taken between 0 and 1, represents the amount of magnetic energy transfer to the particles. This expression allows us to determine the energy gained for one particle (electron or proton) by the following expression:

$$\varepsilon_{e,p} = eE_{AR} < \Delta l_{e,p} > P(\Delta l) \tag{2.2}$$

where Δl is the acceleration length for one particle and the index e or p represents the electron or proton energy gained. $P(\Delta l)$ is the density probability of the particle acceleration length. By inserting equation 2.1, we obtain the following electron energy gained:

$$\varepsilon_e = \alpha \frac{B_{free}^2}{2\pi n(1+\beta)} P(\Delta l) \tag{2.3}$$

where $n = n_e/2 = n_p/2$ is the plasma density and β is defined as the ratio of the average acceleration lengths. The complete determination of the particle energy gained imposes the knowledge of β and $P(\Delta l)$. In the following, we assume $\beta = 1$ for simplicity reason and thus $\varepsilon_e = \varepsilon_p = \varepsilon$. The acceleration length is given by:

$$P(\Delta l) = k_1 (\Delta l)^{-\delta} \tag{2.4}$$

We consider now several DR leading to a "gas" of acceleration regions with different values of magnetic energy incoming into each AR. Particles (electrons and ions) are accelerated in a different direction into each AR. Thus, electrons and ions are accelerated in the same direction outside of the global acceleration region. The total particle energy distribution outside of the global acceleration region corresponds to the sum of the particle energy distribution in each AR. In other words, every particle interacts only with one acceleration region. We consider that the magnetic energy incoming into the different AR evolves in a power law distribution (Vlahos et al. 2004 and references therein):

$$P(B_{free}^2) = k_2 (B_{free}^2)^{-\zeta} \tag{2.5}$$

Thus, the electric field distribution is given by:

$$P(E_{AR}) = k_3 (E_{AR})^{-\zeta} \tag{2.6}$$

Where k_1, k_2 and k_3 are constants. The total particle energy distribution can be written as:

$$N(\varepsilon)_{total} = \sum_{i=1}^{n_{AR}} N(\varepsilon)_{AR,i} \tag{2.7}$$

Where n_{AR} is the total number of AR and N(ε) is given by equations 2.3 and 2.4.

3 Results

We compute the total particle energy distribution given by equation 2.7 for different values of n_{AR}. For each AR, we select randomly α between 0 and 1. Particles are injected in the acceleration volume with an initial Maxwellian distribution with a temperature of 10^6 K and with initial velocities in the range $0 < v < 8v_{th}$ where v_{th} is the thermal velocity. The particle energy distribution for electrons and ions is calculated with a density of n=$10^{10} cm^{-3}$. We consider only super Dreicer events, thus we normalize the minimal value of the electric field distribution to the Driecer electric field equal to $5.5\,10^{-4} V.cm^{-1}$.

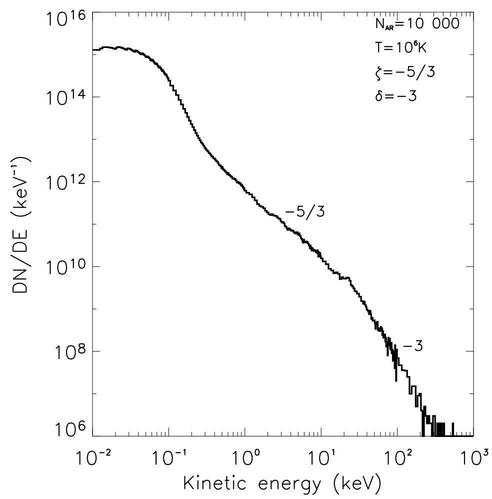

Fig. 1. Kinetic particle energy distribution obtained for n_{AR}=10 000, ζ=5/3 and with a distribution of particle acceleration length given by a power law of spectral index δ=3. The temperature of the injected maxwellian is 10^6 K.

Figure 1 shows the particle energy gain distribution obtained from these 10 000 AR. Several results can be drawn from this figure:

1. The distribution of the particle energy gain can be divided in three parts. The first one corresponds to the thermal plasma injected with a temperature of 10^6 K corresponding to a peak in the particle energy distribution at 43 eV. The second part of the spectrum is a power law of spectral index -5/3 corresponding to the spectral index of the magnetic energy release process. The last part of the spectrum corresponds to the particle energy distribution accelerated from the AR of larger electric field. This part corresponds here to a power law of spectral index equal to -3. The formation of this part of the spectrum is discussed in the next section.

2. The break in the kinetic energy distribution occurs at ε_{break} which corresponds to the energy gain of the particles of lower acceleration length in the AR of larger electric field value. Thus, ε_{break} is given by:

$$\varepsilon_{break} = eE_{max}\Delta l_{min} \tag{3.1}$$

In this case, the maximum value of electric field ($10^5 E_D$) is $55\,V.cm^{-1}$ and the minimum acceleration length is 550 cm. The resulting energy break occurs at 27.5 keV.

We consider now that some of the particles undergo multiple interactions. Figure 2 shows the particle energy distribution obtained with 10% of the total number of particles that undergo several interactions. Particle accelerated by this stochatic process add a high energy component in the particle energy distribution, which can leads to the formation of a new break at high energy. Such a break could explain the breaks observed at high energy in several flares.

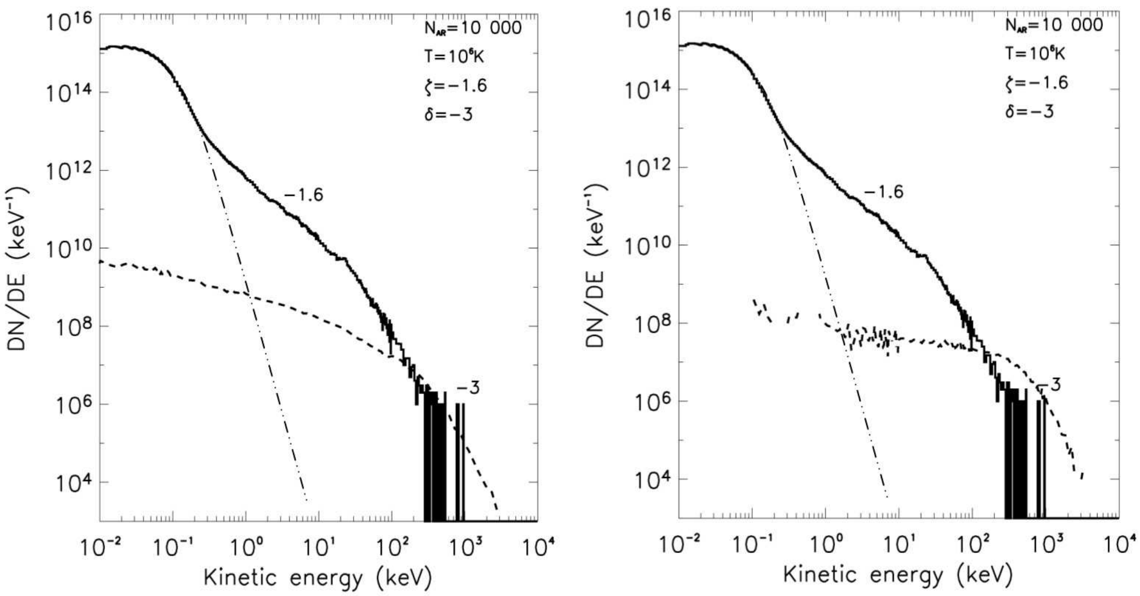

Fig. 2. Kinetic particle energy distributions obtained for n_{AR}=10 000, ζ=1.6 and δ=3. In the left panel, 10% of the total number of particles undergo between 1 and 1000 interactions (dash line). In the right panel, 10% of the total number of particles undergo between 1 and 10 000 interactions (dash line). The dash dot line represents the thermal part of the spectra.

4 Discussion and conclusions

We have presented a theoretical acceleration model that assumes the acceleration of particles that draw their energy from the magnetic energy release in several dissipative regions. One of the new assumption introduced in this paper is that most of the particles are accelerated once (i.e. it is not a purely stochastic process). We use this model to compute the total particle energy distribution.

Outside of the thermal part, we can distinguish three parts in the particle energy distribution. The low energy part is purely due to the magnetic energy release process. The high energy component is due to the particles that undergo multiple interactions. Between these two parts, the particle energy distribution results from the combination of the magnetic energy release and acceleration process.

References

Anastasiadis, A., Gontikakis, C., Vilmer, N., & Vlahos, L. 2004, A&A, 422, 323

Dalla, S. and Browning, P. 2006, ApJ, 640, L99

Dauphin, C., Vilmer, N. and Anastasiadis, A. 2006, A&A, accepted

Dauphin, C. 2006, A&A, submited

Decamp, N. and Malara, F. 2006, ApJ, 637, L61

Dmitruk, P., Matthaeus, W., Seenu, N. and Brown, M. 2003, ApJ, 597, 81

Onofri, M., Isliker, H. and Vlahos, L. 2006, PhRvL, 96, 1102

Vlahos, L., Isliker, H. and Lepreti, F. 2004, ApJ, 608, 540