Evolution of electron energy spectrum during solar flares

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Abstract

Particle acceleration by direct-current electric field in the current sheet has been extensively studied, in which an electric and a magnetic field are generally prescribed, and a power law distribution of the electron energy is obtained. Based on MHD numerical simulations of flares, this paper aims at investigating the time evolution of the electron energy spectrum during solar flares. It turns out that the model reproduces the soft-hard-hard spectral feature which was observed in some flares.

Key words: Sun: flares, acceleration of particles, Sun: magnetic fields
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1 Introduction

Particle acceleration in solar flares is an important issue in flare physics. One of the popular mechanisms states that particles near the reconnection X-point are accelerated by direct current (DC) electric field in the current sheet (see Miller et al., 1997; Aschwanden, 2002, for reviews). The electric DC-field acceleration mechanism was first studied by Speiser (1965) in the context of the geomagnetic tail, and applied later in solar flares by many researchers (e.g., Holman, 1985; Litvinenko and Somov, 1993). Theoretical analysis and numerical simulations of the DC acceleration mechanism generally indicate that the accelerated electrons present an energy spectrum with a power law distribution. For example, Litvinenko (1996) analytically obtained a spectral index $\delta = 2$ for charged particles accelerated in a reconnecting current sheet (RCS). Zharkova and Gordovskyy (2005) estimated the indices $\delta$ to be in the range of $2.0 - 2.2$ for electrons in the non-neutral RCS with a non-zero longitudinal component of the magnetic field, i.e., with a guiding field. With the...
guiding center approximation, Wood and Neukirch (2005) found \( \delta \approx 2.6 \) for electrons. Full orbit test-particle simulations by Hamilton et al. (2005) show \( \delta = 2.4 \pm 0.1 \) for electrons accelerated in the electro-magnetic field obtained from an analytic solution to the linearized MHD equations for reconnecting modes at a magnetic X-point.

While, many of these groups (see, however, Hamilton et al., 2005) prescribed a steady electro-magnetic field with an X-type configuration, and little has been done to investigate the time evolution of the electron energy spectrum in solar flares. In this paper test particle simulations are performed in order to investigate the temporal evolution of the electron energy spectrum using a self-consistent time-dependent electric and magnetic fields, which are obtained from 2.5-dimensional MHD numerical simulations as done in Chen and Shibata (2000).

This paper is organized as follows. A description of the simulation model and numerical method are presented in Section 2. The numerical results are presented in Section 3, which is followed by discussions in Section 4.

2 Numerical method

2.1 Electric and magnetic fields

Based on the strong correlation between reconnection-favored emerging flux and filament eruptions/CMEs, Chen and Shibata (2000) performed 2-dimensional MHD simulations and proposed an emerging flux trigger mechanism for CMEs, where the reconnection between emerging flux and preexisting coronal field triggers the loss of equilibrium of the flux rope system. A current sheet forms as the flux rope rises. The reconnection of the current sheet gives rise to the fast eruption of a CME in the large scale and a two-ribbon flare in a smaller scale.

In this paper, we extend this CME flare model to 2.5-dimensions, i.e., a uniform third component of the magnetic field \( B_z \) is introduced in the initial conditions. As in Chen and Shibata (2000), the characteristic values for the temperature and density are \( T_0 = 10^6 \) K and \( n_0 = 10^9 \) cm\(^{-3}\). The plasma \( \beta \) around the flux rope is 0.01, hence the in situ magnetic field is \( \sim 26 \) G and the local Alfvén speed is 575 kms\(^{-1}\). The length scale for MHD simulation is \( 10^4 \) km, and the corresponding Alfvén time scale is \( \tau_A = 16.1 \) s. The dimensionless value of the third component of the magnetic field, \( B_z \), is equal to 0.1, i.e. 2.6 G. The resistivity is distributed in a rectangular area, \(|x| \leq 0.1\) and \(|y-y_n| \leq 0.4\), with the dimensionless form \( \eta/(\mu_0 v_0 L_0) = 0.02 \cos(5\pi x) \cos(5\pi (y - y_n)/4), \)
Fig. 1. Evolution of the CME/flares. The solid lines correspond to the magnetic field, the arrows to the velocity, and the grey scale to the temperature.

where the cosine functions are adopted to ensure that the derivative of the resistivity is smooth everywhere, and $y_n$ is the height of the reconnection X-point. Note that the coordinators, $(x, y)$, are normalized by $L_0$. For simplicity, the gravity and heat conduction are ignored; therefore, the dimensionless numerical results are independent of the length scale, as mentioned in Chen and Shibata (2000).

Fig. 1 plots the temporal evolution of the magnetic field, velocity field, and temperature, which shows that the flux rope loses its equilibrium and begins to rise as the emerging flux cancels the preexisting coronal field in the filament channel. A current sheet forms as the field lines are stretched by the rising flux rope. The reconnection of the current sheet reinforces the eruption of the flux rope. As depicted in Chen et al. (1999), the reconnection rate is defined by $d\psi_n/dt$, where $\psi_n$ is the magnetic flux function at the neutral point. Fig. 2 depicts the temporal evolution of the reconnection rate, which can be divided into three phases, i.e., the rise phase, the peak phase, and the decay phase, where the peak phase corresponds to the impulsive phase of the soft X-ray light curve of solar flares. We select three times as indicated by the arrows in the figure, which are representative of the three phases. The corresponding electric and magnetic fields are adopted from the MHD simulations, where the magnetic field is directly obtained from the numerical results, whereas the electric field is derived from the Ohm’s law in the MHD theory with the dimensionless form

$$\mathbf{E} = \eta \nabla \times \mathbf{B} - \mathbf{v} \times \mathbf{B},$$

where $\mathbf{E}$ is the electric field, $\eta$ is the resistivity, $\mathbf{B}$ is the magnetic field, and $\mathbf{v}$ is the plasma velocity.
2.2 **Test particle simulation**

From a theoretical point of view, a reconnecting current sheet could be as thin as of the order of 10 m in solar flares. However, owing to the limited spatial resolution in MHD simulations, the reconnecting current sheet is generally several orders of magnitude thicker, which makes test particle simulations unfeasible. In order to compromise between the much different length scales, and also noticing that the dimensionless results in MHD simulations are independent of the length scale, we re-scale the resistivity region, as enclosed by the small rectangular near the reconnection X-points in Fig. 1, by a new length scale, $l_0 = 50$ m. It should be noted that after such a re-scaling, the electric field (or the reconnection rate) remains unchanged. In the test particle simulation, electrons are uniformly distributed into a rectangular region around the reconnection X-point: $|x| \leq 0.1$ and $|y - y_n| \leq 0.4$, as indicated by the small rectangular near the X-point in Fig. 1. As an approximation, the electric and magnetic fields are considered to be steady during the electron accelerations since the time scale of the latter is much smaller than that of the evolving MHD process. The initial velocity distribution for the electrons is Maxwellian with the local plasma temperature superimposed on the plasma bulk velocity.

The motion of each electron is then calculated by numerically solving the following relativistic Lorentz equations

$$\frac{d}{dt}(\gamma m_0 \mathbf{v}) = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}), \quad (2)$$

and

$$\frac{dx}{dt} = \mathbf{v}, \quad (3)$$
where $\mathbf{x}$ and $\mathbf{v}$ are the particle position and velocity vectors, respectively, $\gamma = 1/\sqrt{1 - v^2/c^2}$ is the Lorentz factor, $m_0$ and $q$ are the rest mass and the charge of the electron, respectively, and $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields as obtained in the previous subsection.

The 4th-order Runge-Kutta-Fehlberg (RKF45) scheme is used to solve the above equations, where the time step ($\Delta t$) is adaptive. In order to get smooth energy spectra, $2 \times 10^5$ test particles are simulated.

3 Numerical results

Under the Lorentz force, some electrons are accelerated and then propagate away from the initial rectangular region, with around half moving upward and the other moving downward. For simplicity, we consider the downward electrons only. The evolution of energy spectrum of these electrons is shown in Fig. 3. Each spectrum can be fitted with a power law function of the form $f(E) \propto E^{-\delta}$, which is indicated by straight lines superposed on the spectral profiles. Note that only the relatively straight part of the spectral profiles in the energy range of tens of keV is fitted. It is seen that the spectral index ($\delta$) changes as 7.6, 7.1, and 6.0 at the three consequential times, $t = 35$, 64, and 99 $\tau_A$. Based on the thick-target model of non-thermal electron bremsstrahlung radiation (Brown, 1971), the corresponding hard X-ray (HXR) spectral indices ($\gamma$) are 6.6, 6.1, and 5.0, respectively. This means that in our model simulation, the evolution of the HXR spectrum presents a soft-hard-hard feature.
4 Discussions

The evolution of the HXR spectrum in most flares shows a soft-hard-soft behavior across the impulsive phase of the soft X-ray flares, which is expected since the reconnection rate peaks at the impulsive phase. However, some flares, which are called Type C flares (Dennis, 1988), present a soft-hard-hard variation, which remains to be a puzzle for a long time. We performed test particle simulations of the electron acceleration based on a self-consistent electromagnetic field, which is adopted from the MHD simulations of the CME/flare model proposed by Chen and Shibata (2000). Surprisingly, the resulting energy spectrum of the DC-accelerated particles reveals a soft-hard-hard variation across the impulsive phase. Our preliminary research indicates that the longitudinal component of the magnetic field in the current sheet is crucial in determining the behavior of the energy spectral evolution. The detailed investigation of the $B_z$ effect is devoted to a future paper, in which we try to clarify when a flare appears as a normal type and when it appears as a Type C one. According to our recent parameter survey (Liu et al., 2007), a stronger magnetic field or a larger length scale would decrease the spectral indices in order to account for the typical indices in type C flares, i.e., $2 - 5$ (Dennis, 1988). While, the effects of various parameters on the spectral evolution, including those in types A and B flares (Dennis, 1988), will be studied in detail in our future paper.

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