Monte-Carlo simulation of particle acceleration in impulsive phase of solar flares

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Abstract

We investigate particle acceleration in solar flares, which may be attributed to radio, hard X-ray and γ-ray emissions during their impulsive phase. The magneto-hydrodynamics picture utilizing magnetic reconnection, in which the fast shock is naturally formed. Such fast shock must be efficient accelerator of electrons and protons by first-order Fermi acceleration because the shock has oblique magnetic configuration where the enhancement of the shock acceleration is suggested and the acceleration region is sandwiched by slow shock which reflects the particles. We simulate the particle acceleration using Monte-Carlo method under test particle approximation and find that the particles are accelerated to power-law distribution. The resultant spectral index is sensitive to angle between the magnetic field and the shock normal and to compression ratio of the fast shock.

1. Introduction

Recent detail observations for solar flares have presented many evidences for production of high energy particles. Especially, energy spectra on radio, hard X-ray, and γ-ray energy ranges show nonthermal emission during impulsive phase which suggests that electrons should be accelerated to power-law energy spectrum in that phase. Since both high energy electrons and protons (ions) appear in various scale flares from impulsive flare to long-duration event, the acceleration mechanism in solar flare can be available both particle and cover wide scale range. A first order Fermi acceleration (diffusive shock acceleration) has been proposed as such acceleration mechanism [1].

Yohkoh observations in 90s strongly suggest that magnetic reconnections in the corona trigger solar flares, and that magneto-hydrodynamic (MHD) slow-mode shocks attached to reconnection diffusion region (X-point) convert magnetic energy to plasma kinetic energy and thermal energy [2]. The downward plasma out-flow from the diffusion region causes footpoint hard X-ray sources. Furthermore, discovery of an impulsive loop-top hard X-ray source above soft X-ray loop

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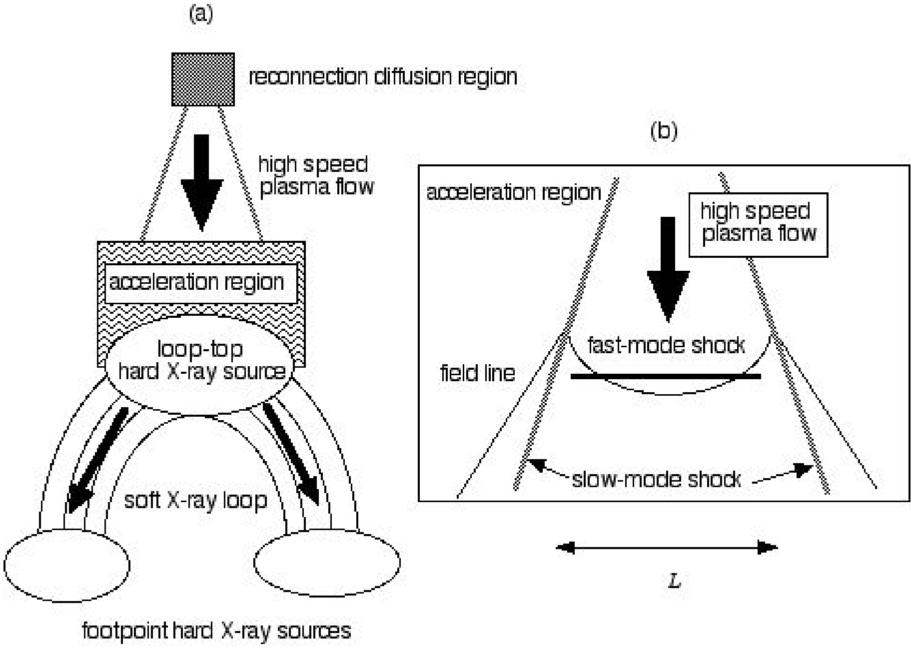

Fig. 1. The magneto-hydrodynamics picture of solar flare.

[3] support this story. The schematic picture of this scenario is showed in Fig.1 (a). This high speed plasma flow sandwiched by slow shock is regarded as the most likely acceleration site for the high energy particles [4].

The high speed plasma collides with magnetic loop (or solar surface) to form fast-mode shock. The geometry of magnetic field at the fast shock naturally produces oblique shock configuration as showed in Fig.1 (b) in which magnetic field crossing shock surface inclines to plasma flow. From this point of view, Tsuneta and Naito [5] submit new acceleration model to indicate following three main results, (1) the plasma is already heated by reconnection before acceleration to solve injection problem, (2) the acceleration is enhanced by oblique shock [6,7] to surpass particle cooling with Coulomb collision, and (3) slow shocks standing side of acceleration region work to confine accelerated particles by magnetic mirror effect. However, in previous paper [5] we could not evaluate the energy spectrum of the accelerated particles because it depends on various effects. In this paper, we calculate the energy spectrum by numerical simulation for some field configuration and compression ratio of fast shock on the basis of Monte-Carlo method [7]. As a result, we obtain the spectral indices of accelerated particles, which are evaluated in some observations.

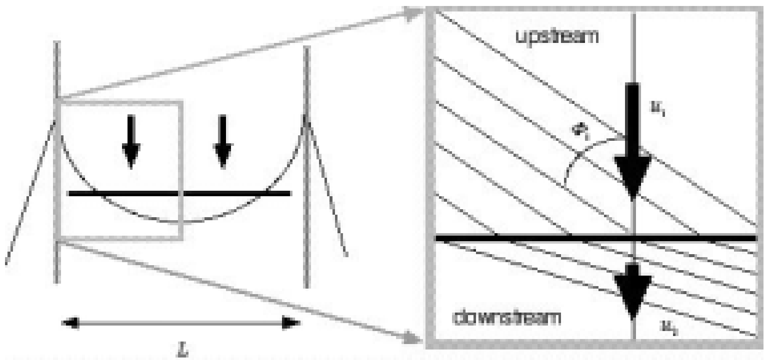

Fig. 2. Approximation of acceleration region.

2. Method

We calculate energy spectrum of accelerated particles on the framework described in Fig.1. Surface of fast shock and acceleration region are limited by two slow shocks facing each other, although in the standard shock acceleration theory they are assumed to extend infinitely. Therefore, we adopt Monte-Carlo simulation to include effect of these boundary. We approximate the acceleration region to square box shown in Fig.2, of which left side boundary corresponds to slow shock where particles reflect due to magnetic mirror effect. The right side boundary is treated as an elastic wall. We adopt test particle approximation. Since the shock acceleration may operate equally both electron and proton are accelerate, we describe their energy with Lorentz factor γ.

We investigate following two parameters: compression ratio r and shock angle Φ_1. r denotes compression ratio of fast shock and is defined by $r = u_1/u_2$ where u_1 and u_2 are plasma speed of upstream and downstream, respectively. It depends on adiabatic index and Mach number of plasma, and is speculated from observation as $1.5-3$. The angle between shock normal and the field line crossing the shock in upstream side (see Fig.2) is denoted by Φ_1.

3. Results

Adopting $u_1 = 10^3$ km s^{-1}, $L = 10^4$ km, $\tau = 300$ km, $E_0 = 5$ keV, where L is width of acceleration region, τ particles mean free path, and E_0 initial energy, we simulate 5×10^3 particles. Integrating over acceleration region and time, we obtain energy spectra $F(\gamma-1)$ shown in Fig.3 by $(\gamma-1)F(\gamma-1)$, where particle energy is described by kinetic energy $\gamma - 1$. In Fig.3 (a), r is fixed at 2.0 and $\cos\Phi_1$ is changed by 0.40, 0.20, 0.10, and 0.05; in Fig.3 (b), $\cos\Phi_1$ at 0.20 and r by 2.5, 2.0, 1.5, and 1.2. Power-law feature emerges in each spectrum, then, we fit the power-law part with $F(\gamma-1) \propto (\gamma-1)^{-\alpha}$.

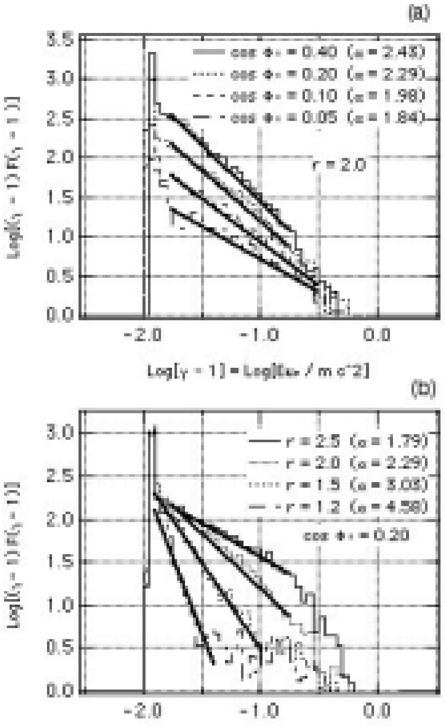

Fig. 3. The energy spectra. Fitted αs are denoted in parenthes.

4. Discussions

In the case of fixed r, spectrum becomes harder for smaller $\cos\Phi_1$, that is to say larger Φ_1 or more oblique shock, as it suggested by [6] [7]. However, magnitude of spectrum at fixed energy gives smaller value for larger Φ_1, because the acceleration time for larger Φ_1 is shorter by the geometry of the magnetic field. In the case of fixed Φ_1, spectrum becomes harder for larger r. In this case, magnitude of spectrum at fixed energy gives larger value for larger r.

Radio, hard X-ray and γ-ray spectra can be speculated from these results.

5. References

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