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Particles Acceleration on Flare Termination Shock

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The solar flare is the mostly erupted activity. The magnetic field reconnection and the fast jet are the mysteries for the solar physics community. In this environment, it is wondering if there is the particles acceleration and how to work. In the present work, we chose a standard solar flare as an example to investigate the probable association with the termination shock scenario. We use a dynamic Monte Carlo method to examine the energy spectrum with the relevance to the flare event. In the termination shock scenario, the thermal energetic particles in the fast jet pushes into the top of the loop for shock formation and acceleration efficiently. As a result, we obtain the detailed energy spectra, structures with different behaviors at the related episodes of the termination shock evolution. Therefore, we predict that there is a impulsive termination shock and particles acceleration.

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1. Introduction

Which solar events are responsible for the production of SEPs most dangerous for Space Weather? What type of events can give rise to extreme SEP enhancements[14, 18]? One can accept the opinion of the large SEPs normalcy originated from the CME-driven shock. However, some large SEPs occasionally are emitted from the solar flare without CME. In this paper we provide modeling efforts related to SEPs, which are born from solar flare termination shock.

Impulsive SEP events are short for less than one day, low intensity and numerous with the average number about 1000/year. Gradual events are long for several days at energies of a few MeV/nuc, rather rare for decades per year, and orders of magnitude more intense in protons than impulsive SEP events. The gradual events, characterized by the largest proton fluxes and therefore of most relevance to Space Weather, are ascribed to acceleration by CME-driven shocks as they propagate through the heliosphere. However, the large SEPs events also can be accelerated in the termination shock formed by the interaction of the solar flare jet and the top of the flux tube of the photosphere. This acceleration processes is similar to the gradual SEPs event.

In gradual events, protons can be accelerated into the GeV range, and, when directed towards the Earth, may lead to neutron monitors (NMs) detecting events at the Earth's surface. These GLEs are the most extreme of solar events, and thus are of special interest to the heliophysics community [1, 19]. Our understanding of energetic solar events and specifically GLEs increased dramatically during solar cycle 23 [11] as a result of advances in instrumentation and an abundance of events to observe. Solar cycle 24, being much quieter than the previous one.

GLE events are one type of large gradual SEP event. In these events, protons and ions are accelerated to very high energies with intensities often 10-100 times larger than normal gradual SEP events. This suggests that the underlying acceleration of GLE events is the same as that operating in normal gradual SEP events - the diffusive shock acceleration (DSA)[9, 7]. The standard DSA mechanism was born in 1970s [2, 15, 4, 6]. Its application in the interplanetary shock can CME-driven shocks have been taken by various authors. Lee [16, 17] solved the coupled particle transport and wave action equations. The approach provided a self-consistent formalism for evaluating $Alfvén$ wave amplification and particle energization at a quasi-parallel shock. For investigating why do termination shock produces larger intensity and higher energies than the normal impulsive SEPs? Here we proposed a flare "termination shock" scenario for SEP events.

2. Model

In the late 1970s, many authors [2, 15, 4, 6] introduced the test-particle theory of particle acceleration at strong collisionless shocks due to the first-order Fermi mechanism. However, quantitative estimates soon pointed out that this DSA mechanism may be so efficient that the backreaction of the accelerated particles on the shock dynamics cannot be neglected. The obvious theoretical challenge is how to model effectively the full shock dynamics. Modelling shocks with efficient particle acceleration using plasma simulations [particle-in-cell (PIC) and hybrid] is extremely computationally expensive for several reasons. First, the energies of charged particles participating in the process range from the low thermal energies of cold plasma to the ultrarelativistic energies of cosmic rays (CRs), and both extremes of particle spectra are dynamically important if acceleration is efficient (see e.g. Vladimirov et al. [22], for estimates of computational requirements). Secondly, simulations need to be done in three dimensions because of the possibility of non-physical suppression of important processes in one- and two-dimensional simulations (see e.g. Jones et al. [12]). Therefore, approximate methods must be used to model efficient particle accelerating shocks.

In Monte Carlo simulations, one follows particles scattering off the magnetic irregularities based on an assumed scattering law. As the background flow around a one-dimensional shock which is assumed to be in a steady-state, Ellison et al. [9] used steady-state Monte Carlo method to calculate the particle spectra accelerated in the parallel component of Earth's bow-shock and successfully compared them with observational data. They showed that the agreement between simulation results and observed data was quite impressive. But the highest energy accelerated by the shock only goes up to 100 keV due to the small size of Earth's bow-shock. They also showed that the results of Monte Carlo simulations were consistent with those of hybrid plasma simulations. Baring et al. [3] also did the same kind of comparison with the observed data in oblique interplanetary shocks and also came up with excellent agreements. Later Knerr et al. [13], Wang et al. [24, 25] developed a dynamically time-dependent Monte-carlo simulation for the Earth's bow-shock, and give the production of the more than 4MeV energetic particles at the high energy "tail".

In an effort to complement and extend such studies, we focus on the flare termination shock on the top of the photosphere. So a dynamical Monte Carlo model for the study of jet-driven collisionless shock and their associated particle acceleration is developed. Our termination-shock model using the dynamical Monte Carlo code means that the angular momentum diffusive behavior is based on a prescribed assumption obeying a certain distribution in the scattering process. Under the isotropic scattering angular distribution, we can readily follow particles as they move about the shock and scatter in the background flow. In this isotropic scattering model, particle injection and escape are treated in a natural, self-consistent manner.

This multiple-shock Monte Carlo simulation presented here employ the prescribed isotropic scattering angular distributions based on earlier dynamical simulations done by Knerr et al. [13] to study Earth's bow shocks. Since the pitch angle scattering law models particle scattering off the collective fields of the plasma, calculation of the electric and magnetic fields is unnecessary and is omitted. Under the assumption of the isotropic scattering angular distributions algorithm, particles scatter off the infinitely massive scattering centers elastically with a random angle between 0 and θ_{max} in their local flow frame. In addition, we assume a constant scattering time (i.e., the mean time between two scattering events) for all particles, which implies particles' mean free paths are proportional to its velocity. This idea that such a simple law can be used to describe the entire scattering process was postulated by Eichler [8], based on the two-stream instabilities work done by Parker [20]. Put simply, it is assumed that the turbulence generated by both energetic particles streaming in front of the shock and by thermal particles produces nearly elastic scattering for particles of all energies in diffusive shocks.

3. Termination Shock Simulation

This model describes the termination shock driven by the flare jet interacted with the top of the photosphere. An SEP event is produced by the collisionless shock via diffusive shock acceleration

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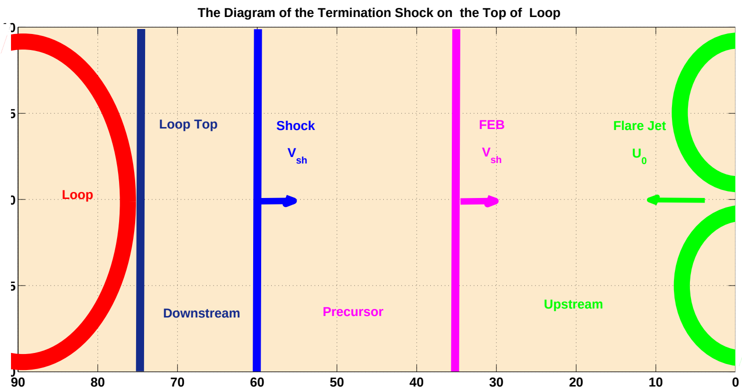

Figure 1: In the simulation box of the termination shock on the top of loop, the left reflective wall represents the loop top produce termination shock(representing by the blue vertical bar) propagating from the left loop to the right of the simulation box. The termination shock with the FEB evolve into the simulation box by smooth movements from the left to the right. At the right of the simulation box, the flare jet originated from the X-point of the magnetic reconnection with a high speed.

mechanism. This mean that the effective SEP event will be produced at the beginning of the origin of the solar flare, which different from the SEPs originated from the CME-driven shock at the interplanetary space. In the flare region, there is the enough large magnetic field up to ∼100Gauss, and high speed of the flare jet up to a few 1000kms^{-1}.

Fig. 1 shows a schematic diagram of the termination shock model. The left reflective wall represents loop top of photosphere and produce the shock. Termination shock propagates from the loop-top at the left boundary of the simulation box to the right boundary. The shock propagating into the inner of the simulation box with a relative bulk speed of U_0, the blue vertical bar at the simulation box indicates the shock, the pink vertical bar represents the free escaped boundary (FEB), respectively. Initially, the upstream bulk flow speed of the shock is U_0 and the downstream bulk flow speed of shock is zero at the rest shock reference frame. So the initial thermal ions inside the upstream of the shock can be as the seed of the energetic particles for accelerating by the Fermi mechanism at the shock front via many crossing cycles. We apply a dynamic Monte Carlo technique to simulate this termination shock scenario in detail for investigating the total energy spectral property.

We consider a quasi-parallel shock related with a flare SEP event where the supersonic down flows moves from X-point of the magnetic reconnection site to the top of the lower flux loop along the x-axis direction. With the termination shock propagating from the loop top along the x-axis to the upper solar atmosphere. In order to investigating the enhancement intensity of this associated flare SEP event, we use a particle simulation method to reconstruct the energy spectrum of the related SEP event. Here, we apply a nonlinear dynamic Monte Carlo code to simulate termination shock scenario containing the back-reactions of the accelerated particles on the upstream sub-shock in front of the shock. In this model, the shock produces accelerated ions from the upstream by Fermi mechanism. According to the ordinary observations, we can take the initial upstream bulk speed with the value for U_0==1000kms^{-1}, the relative bulk speed of the shock.

In this Monte Carlo method, we apply an initial number density of particles n_0 in the upstream bulk flow of the shock, which obeys a Maxwellian distribution with a thermal speed υ_{L0}. The shock remains the relative bulk speed $\Delta U = U_0$ between the upstream and downstream bulk flow. The total simulation time is t_{max}. During the period of the simulation time, the termination shock undergo particles injection, the magnetic field amplification and the energetic ions' acceleration processes. In the rest shock reference frame, the background flare jet bulk speed hold on the value of U_0. Here, we suggest the termination shock as a single flare jet driven shock would produce a normal power-law energy spectrum on the associated SEPs.

The scattering process is usually modeled by some dependencies of the mean free path λ_{mfp} of the particles on momentum p in most particle simulation cases. Thus, in order for the acceleration to be efficient, a large number of shock crossings back and forth on the shock front are required. Shock particle acceleration therefore depends on the scattering process which is clearly a stochastic process, depending on the presence of scattering centers upstream and downstream and on the random changes in the scattering angle. It assumes that the scattering is elastic and isotropic for conserving energy. This mechanism always works until the gyroradius of the accelerated particle becomes large enough for exceeding the size of the system or the energy of the particle becomes large enough for producing scare back-scattering. In order to experience the first scattering, the particle must initially already possess a gyroradius much larger than the entire width of the shock transition region. Only when this condition is satisfied, the shock will behave like a slightly thin discontinuity separating two regions of very different bulk speeds. A particle crossing back and forth over such shock can become aware of the bulk difference in speed and gain energy additions. In fact, for entering into the Fermi acceleration mechanism a particle must be pre-heated until its gyroradius becomes larger than the width of the shock [21, 30].

Monte Carlo method applies a scattering law for particle diffusive processes on shocked plasmas, and the details of the scattering process are described in Wang et al. [23, 26, 27, 28, 29]. We assume that the particles scatter elastically off the background scattering centers with their scattering angles obeying an isotropic distribution in their local frame. In this scattering scenario, the assumption of elastic scattering requires that scattering centers are frozen into the background fluid; Simultaneously, the assumption of a constant collision time for all particles requires the particle's mean free path is proportional to its local velocity in the local frame[10].

In this termination shock simulation box, all the simulated parameters are listed in Table 1. According to the observations, we adjust the observed parameters for applying the appropriate simulated parameters. We present the scaled values of the parameters as follows. The background flare-jet bulk speed is U_0=1000kms^{-1}; The initial local thermal velocity is υ_{L0}=20.0kms^{-1}. The scattering time is τ_0=0.1349seconds. The box size is chosen to be the X_{max}=0.1R$_\odot$ for ensuring the termination shock production within the box (where R$_\odot$ is the solar radius, about 109 times of the Earth radius R$_e$). The total time of the simulation is chosen to be t_{max}=220.67seconds and long enough for producing the enhancements of the SEP event. Accordingly the time step is set to be dt=6.1$\times$10^{-3}seconds.

The above scaled values of the parameters are corresponded to the follow dimensionless parameters, respectively. The relative upstream bulk flow speed of each shock U_0=0.75; Initial local thermal velocity $\upsilon_{L0} = 0.015$; The constant of the collision time τ=0.733; The total size of the box X_{max}=300; The total simulation time t_{max}=1200; The time step δt=1/30. These dimensionless values can be scaled by the distance (X), time (t), and velocity (U) scaling factors: X_{scale} =0.1$R_\odot$/300,

Table 1: The Simulation Parameters

Physical Parameters	Dimensionless Values	Scaled Values
Upstream bulk speed 0	U_0=0.75	1000kms^{-1}
Initial thermal velocity	υ_{L0}=0.015	20.0kms^{-1}
Scattering time	τ_0=0.733	0.1349s
Box size	X_{max}=300	0.1$R_\odot$
FEB size	FEB=105	0.035$R_\odot$
Total time	t_{max}=1200	220.67s
Time step size	dt=1/30	6.1×10^{-3}s
Magnetic Field	B_{up}	48G
Number of zones	m_x=600	...
Initial particles per cell	n_0=500	...

Notes: The $R_\odot$ is solar radius(here, $\sim$ 750Mm). The scale factors for distance, velocity, and time are X_{scale} = 0.1$R_\odot$/300, U_{scale} = 1000kms^{-1}/0.75, and T_{scale} = X_{scale}/U_{scale}. The dimensionless values and the scaled values can be transformed by the scaled factors each other.

U_{scale} = 1000kms^{-1}/0.75, and t_{scale} = X_{scale}/U_{scale}, respectively. In addition, we give the simulation box grids of m_x=600, and the initial density of particles in each grid is n_0=500. The total number of the particles in the simulation box at the end of the simulation archives to more than one million particles.

4. Energy Spectra

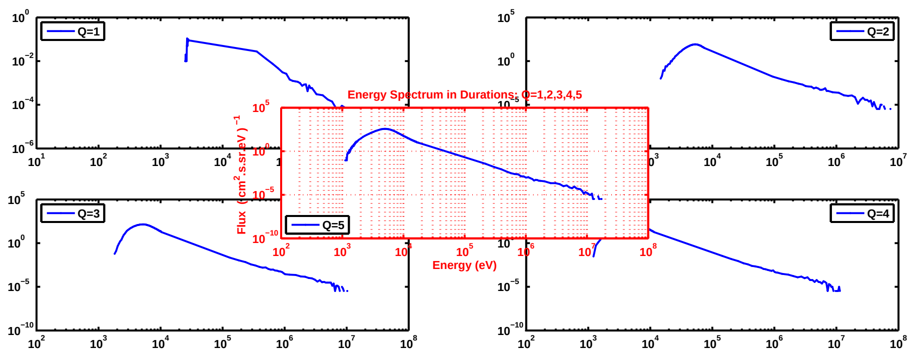

Figure 2: The simulated energy spectrum calculated from the termination shock scenario in the time durations of Q=1,2,3,4 and 5, respectively. The maximum energy particle up to ∼20MeV. The total energy spectra show a single power law with an initial thermal peak.

Fig.2 shows the power-law energy spectra with an initial thermal peak for particle fluxes in the different simulation durations Q=1,2,3,4,and 5, respectively. At the end of the simulation time duration of Q=5, the maximum energy particle up to $\sim$ 20MeV. In this flare-jet termination shock scenario, an SEP event associated with flare is produced and generate a power-law energy spectra effectively. From the Fig.2, the energy spectrum covers the total energy range up to 20MeV. The suprathermal particle "tail" is shown at the energy range less than $\sim$ 100keV. At the energy range from the 100keV to ∼20MeV, the energy spectrum show a single smooth power-law shape with an index of Γ ∼2.5 at the simulation time duration Q=5.

5. Summaries and Conclusions

In summary, we simulate the flare termination shock system for predicting the proton spectrum directly. We obtain the total energy spectrum covering the energy range up to 20MeV. We also find the simulated energy spectrum exhibits the energy spectral "smooth" power law at the energy range up to ∼20MeV. There would be new idea for SEPs origination, beside of the gradual SEPs originated from the CME-driven shock at the interplanetary space, there is new origination from the solar loop top termination shock, which is more early than gradual cme-driven shock. This investigation will play important role for forecasting the space weather, and provide the important information on the analysis of the data for SEPs observations according to solar events with companied CME or without companied CME. These processes can be observed from the gamma ray emission and the hard X-ray emission from the spacecrafts and multiple micro-waves observations on the ground-based instruments. We will forward to investigate the termination shock acceleration for earlier information than the interplanetary CME shocks.

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