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Particles Acceleration on Twin-shock of Solar Flare Jets

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The solar flare is usually erupted continuously. The fast jets interaction are the mysteries for the solar physics community. In this environment, it is wondering if there is the termination shocks interaction and how to work on the particles acceleration. In the present work, we chose one solar flare event as an example to investigate the probable association with the termination shock collisions. We use a dynamic Monte Carlo method to examine the energy spectrum with the relevance to the twin flare event. In the twin-flare shock scenario, the thermal energetic particles in the fast jet pushes into the top of the loop for twin-shock formation and acceleration efficiently. As a result, we obtain the detailed energy spectra, structures with different behaviors at the related episodes of the twin-flare shock evolution. Therefore, we predict that there exists a more efficient twin-flare shock model on particles acceleration.

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1. Introduction

Historically flares and filament eruptions were the only known major transient features in the solar atmosphere. High-energy particles from the Sun were first observed [7] as sudden increases in intensity in ground-level ion chambers during the large solar events of February and March 1942. So SEP events were considered as a consequence of flares until the 1970s. Since the discovery of CMEs by Kahler et al. [12, 13, 11], a bimodal framework for the interpretation of SEP events has emerged, SEP events have been classified into the impulsive and gradual solar events (e.g. flares and CMEs) [3, 19, 20]. Thereafter, there are a substantial amount of statistic studies and observational evidence to indicate that gradual SEP events can be associated with CMEs. For example, there is a linear correlation between the logarithmic of proton peak intensity and the logarithmic of speed of their associated CME [14]. In the upstream region of a shock associated with the Bastille Day CME, the excitation of hydromagnetic waves with power spectral density levels well above the levels in the ambient solar wind were observed by [1] with the magnetometer on board the Advanced Composition Explorer (ACE). As another empirical association, the peak flux of the SEP is rather correlated with the CME speed than with the X-ray flare peak flux [9].

However, there are a few GLE events show that the SEPs just associated with the solar flare but without the CME event. To investigating this phenomena, here, we would suggest a twin-flare model. Actually, Li et al. [16] have proposed a "twin-CME" scenario for GLE events and large SEP events upon solar cycle 23. In our twin-flare scenario, two flares go off closely in time from the same active region (AR). The preceding flare jet drives a termination shock which generates a very turbulent downstream and produces the seed of the normal energetic particles. As the posterior flare jet plunges into the strong turbulent region downstream of the preceding termination shock, it will accelerate them to very high energies[4, 8]. Depending on whether there is reconnection between the magnetic field turbulence occurred on the posterior jet-driven shock and that produced by the preceding flare jet, the pre-accelerated ions inside the preceding flare jet's driver can be processed by the posterior flare jet, leading to an enhancement of ions that are compositionally [17]. In addition, Gou et al. [10] analyze a model on the impulsive flare on May 13th 2013. They deduced that "two-step" magnetic reconnections between double consecutive flare jets play major roles on the production of the impulsive SEP event. Because of they have found the RHESSI observations shown a strong burst of hard X-ray (HXR) and γ-ray emissions with hard electron spectra, exhibiting a "soft-hard-harder" behavior.

2. Twin-flare Shock Model

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. [6] 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

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simulations. Baring et al. [2] 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. [15] 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 impact of the pileup shocks on the twin-shock wave evolution and propagation. So a dynamical Monte Carlo model for the study of twin parallel collisionless shocks and their associated particle acceleration is developed. Our twin-flare 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.

These twin-flare shock Monte Carlo simulations presented here employ the prescribed isotropic scattering angular distributions based on earlier dynamical simulations done by Knerr et al. [15], Wang et al. [22] to study Earth's parallel 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 velocity. This idea that such a simple law can be used to describe the entire scattering process was postulated by Eichler [5], based on the two-stream instabilities work done by Parker [18]. 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. Twin-flare Simulation

This model describes the twin-flare termination shock interactions of a large SEP event at the loop top of the photosphere, which would trigger off the related GLE event at the Earth atmosphere. This means that there are distinct flares with the same direction at different time in this event.

Fig. 1 shows a schematic diagram of the "twin-flare shock" model. The left reflective wall represents loop top and produce the shocks at the different time. Shocks No.1 and No.2 propagate from the left boundary of the simulation box to the right boundary. After the shock No.1 propagating into the inner of the simulation box with a relative bulk speed of U_{01}, the shock No.2 begins to propagate from the left reflective wall to pursue the shock No.1 with a bulk speed U_{02}, consequently. The two blue vertical bars at the simulation box indicate the shock No.1 and No.2 fronts, respectively. Initially, the upstream bulk flow speed of the shock No.1 is ΔU_1 and the downstream bulk flow speed of shock No.1 is zero at the rest shock No.1 reference frame. When the shock No.2 entering into the simulation box, then two shocks begin to have an interaction each other with a relative speed of ΔU_2. Once the rest shock No.1 reference frame turns to the rest shock No.2 reference frame, the upstream and downstream bulk speeds of the shock No.1 should be added an increment of the bulk speed ΔU_2 becoming into the $\Delta U_1 + \Delta U_2$ and ΔU_2, respectively. The upstream

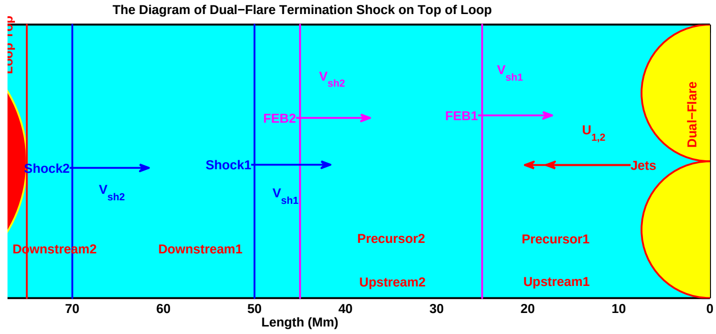

Figure 1: A schematic diagram of the twin-flare termination shock simulation box. The left reflective wall represents the loop top produce shocks No.1 and No.2 (representing by two blue vertical bars) propagating from the left boundary to the right of the simulation box. After a period of time, the flare jet1 produce shock No.1 propagating into the simulation box, then the flare jet2 also produces shock No.2 appearing at the left boundary of the simulation box continuously. The twin-flare shock evolve into the simulation box with a pileup interaction.

and downstream bulk speeds of the shock No.2 correspondingly become the ΔU_2 and zero, respectively. In the "twin-flare shock" scenario, since there exists a relative bulk speed ΔU between the two sympathetic shocks, the downstream bulk flow of the shock No.1 is always compressed by the shock No.2 unless the shock No.2 catches up with and exceeds the shock No.1. So the heating and accelerated ions inside the downstream of the shock No.1 can be as the seed of the energetic particles for re-accelerating by the Fermi mechanism at the shock No.2. We apply a dynamic Monte Carlo technique to simulate this "twin-flare shock" scenario in detail for investigating the integral energy spectral property.

We consider two quasi-parallel shocks related with a large SEP event where the supersonic flows move from X-point site to the loop top along the x-axis direction. With the preceding shock propagating from loop top along the x-axis to the upper photosphere. The posterior shock propagates along the same direction. In order to investigating the enhancement intensity of this associated GLE event, we use a particle simulation method to reconstruct the energy spectrum of the related flare SEP event. Here, we apply a nonlinear dynamic Monte Carlo code to simulate "twin-flare shock" scenario containing the back-reactions of the accelerated particles on the upstream subshock in front of the two shocks, respectively. In this model, the shock No.1 initially produces the heating and accelerated ions as the seed energetic particles for further acceleration when they penetrate into the the shock No.2. The shock No.2 moves forward to the shock No.1 with a relative bulk speed ΔU_2 with the same direction alone x axis. 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 No.1 with a value for ΔU_1=1000kms^{-1} between its upstream and downstream bulk flows, the relative bulk speed of the shock No.2 with a value for ΔU_2=500kms^{-1} between its upstream and downstream bulk flows. Note here, the downstream of the shock No.1 is identity to the upstream of the shock No.2. Here, we apply an initial number density of particles n_0 in the upstream bulk flow of the shock No.1, which obeys a Maxwellian distribution with a thermal speed υ_{L0}. The shock No.1 remains the relative bulk speed ΔU_1 between the upstream and downstream bulk flow till the shock No.2 appears at the left boundary of the simulation box. The total simulation time is t_{max}. After a period of the simulation time, we start the shock No.2 to pursue the shock No.1 from the left boundary of the box with a relative speed ΔU_2. In this "twin-flare shock" scenario, since the posterior jet-driven shock catches up with the preceding jet-driven shock and have a pileup collision at the same direction when they propagate forward into the loop top photosphere, the positive effect of the "twin-flare shock" on the energetic particles would enhance the existing energy spectrum. We predict there probably appears multiple "concave" energy spectrum at a certain energy range on the related SEP event.

Table 1: The Simulation Parameters

Physical Parameters	Dimensionless Values	Scaled Values
Upstream bulk speed 1	U_{01}=0.75	1000kms^{-1}
Upstream bulk speed 2	U_{02}=1.125	1500kms^{-1}
Initial thermal velocity	$\upsilon_{\rm L0}$=0.015	20.0kms^{-1}
Scattering time	τ_0=0.733	0.1349s
Box size	$X_{\rm max}$=300	0.1$R_\odot$
FEB size	FEB=105	0.035$R_\odot$
Total time	$t_{\rm max}$=1200	220.67s
Time step size	dt=1/30	6.1$\times$10^{-3}s
Magnetic Field	$B_{\rm up}$	48G
Number of zones	$m_{\rm x}$=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.

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. [21, 24, 25, 26]. In this twin-flare 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 jet1 bulk speed is U_{01}=1000kms^{-1}; The bulk speed of the flare jet2 is U_{02}=1500kms^{-1}. We define the relative upstream bulk flow speed of the shock No.1 is ΔU_1=$U_{01}-0$=1000kms^{-1}; the relative upstream bulk flow speed of the shock No.2 is ΔU_2=$U_{02}-U_{01}$=500kms^{-1}. The initial local thermal velocity is υ_{L0}=20.0kms^{-1}. The scattering time is τ=0.1349 seconds. The box size is chosen to be the X_{max}=0.1R$_\odot$ for ensuring the "twin-flare shock" interaction within the box (where R$_\odot$ is the solar radius, $\sim$ 750Mm). The total time of the simulation is chosen to be 220.67s 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}s. The magnetic field is $\sim$48Gauss. Particles' free escaped boundary(FEB) size is set as 0.035R$_\odot$.

The above scaled values of the parameters are corresponded to the follow dimensionless pa-

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rameters, respectively. The relative upstream bulk flow speed of each shock ΔU_1= 0.75, ΔU_2= 0.375; 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 dt=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, 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

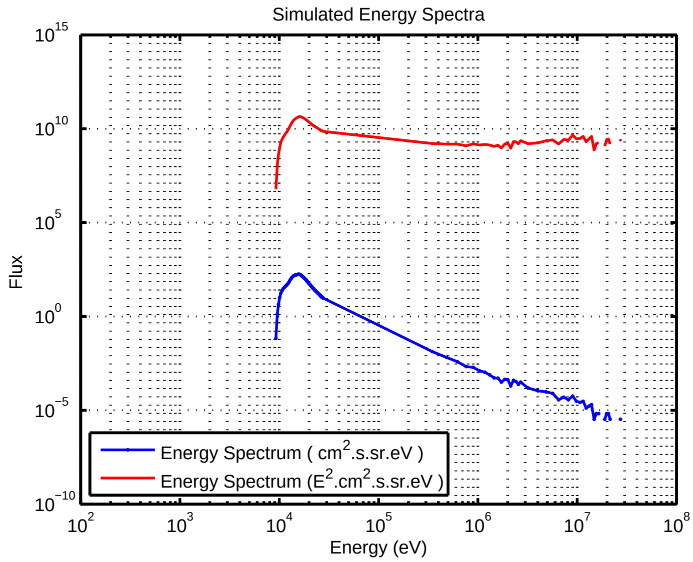

Figure 2: The simulated energy spectrum calculated from the twin-flare shock scenario. The blue curve represents the particle fluxes with the normal representation, the red curve represents the energy spectrum with a specific representation by using a factor of the square of the energy times the flux.

Fig.2 shows the simulated energy spectra at the end of the simulation (Q=5) with two types of representations for the particle fluxes. The blue curve represents the particle fluxes with the energy in normal representation; The red curve represents the particle fluxes multiplying by a factor of the square of the energy E^2 as the representation with the energy E. At the energy range from thermal peak to the maximum energy ∼30MeV, the energy spectral shape exhibits very different behaviors in the specific energy ranges. There seemly exists a maxwellian thermal peak ∼15keV. Then the super-thermal "tail" is shown at the energy range of ∼ 30keV. Later, the particles flux show an power law with a soft index of γ_1=-3.0±0.15 at the range from ∼30KeV to ∼2MeV. During the two fifths of the total simulation time, initial thermal particles in the upstream bulk flow of the shock No.1 enter into the downstream region for diffusive process and lead to the accelerated energy spectrum. This process can be described as the kinetic energies of the upstream bulk flow translate into the thermal particles and accelerated ions, so the super-thermal particles and accelerated ions form as distributed by the power-law range from ∼ 30keV to ∼

2MeV. This soft index also would be contributed by the initial density compression rate r_ρ between the upstream and the downstream of the first shock. For the next stage, when the super-thermal particles and accelerated ions with the size of the mean free path λ_{mfp} large enough to inject from the downstream region back to the upstream region, the super-thermal particles and accelerated ions can be re-accelerated into the higher energetic particles by the twin-flare shock crossings. So at the energy range from $\sim$2MeV to $\sim$15MeV, the energy spectrum becomes a harder than existing power-law slope with an index of γ_2=-1.94$\pm$0.05. In this energy range, the processes can be explained by the fact that the posterior shock begins to enter into the simulation box, and the turbulent magnetic field at the interaction region between the two shocks is amplified abruptly by the energetic particles injecting from the shock No.1 to the shock No.2. This kind of magnetic field amplification (MFA) and the re-acceleration for seed energetic particles can change the existing soft energy spectrum into the very hard energy spectrum immediately. On the next duration at the highest energy range from the $\sim$15MeV to $\sim$30MeV, the energy spectrum shows the power-law slope with a little soft index of γ_3=-2.10$\pm$0.12. After the completion of the merged common region of the “twin-flare shock”, the merged “twin-flare shock” runs like a large “single-flare-jet” driven shock, so the energy spectrum show a behavior of a power law with a little soft index gradually. With the “twin-flare shock” propagating in the upper photosphere, the dissipation of the ambient media can slow down the “twin-flare shock” speed leading to a softer and softer energy spectrum. Totaly, the energy spectrum exhibits different behaviors at the specific episodes of the “twin-flare shock” scenario. Especially, the entire energy spectrum shows a “concave” property at the range from $\sim$30kev to $\sim$15MeV. Largely, the total energy spectral slope produced by the “twin-flare shock” scenario indicates a “soft-hard-hard” mode, which is consistent with the observations[10].

5. Summaries and Conclusions

In summary, we simulate the twin-flare shock system for predicting the proton spectrum directly. We obtain the total energy spectrum covering the energy range up to $\sim$30MeV. We also find the simulated energy spectrum exhibits the energy spectral “concave” point at the energy of $\sim$15MeV. Comparably, we have ever investigated an energy spectrum “break” at $\sim$5.5MeV in our previous converging double-shock model[25]. So, why do the converging shocks in previous study would produce a “broken” energy spectrum and the “pileup” twin-flare shock in present study would produce a “concave” properties in energy spectrum? There would be follow reasons: (i) According to the diffusive shock acceleration theory, the acceleration efficient is determined by the diffusive coefficient[21, 28]. The attainable highest energy particle is depended on the diffusive length of particles scaled by the size of the precursor region[22, 23, 24]. At the converging shocks, the precursor region size will be shorten and fewer and fewer high energy particles gain energies resulting a softer energy at the high energy “tail”[25, 26, 27]. (ii) But in the twin-flare shock scenario, the two shocks interaction can extend the precursor region size and enhance the existing accelerated particle distribution. The pre-accelerated particles caused by the first shock, penetrate into the posterior shocks for re-accelerating and modifying the existing power-law multiply to become a complicated energy spectrum. These processes can lead to a“concave” shape on the energy spectrum.

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