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Comparison of the energy spectra between single shock and converging double-shock

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Observations show that there are proton spectral "breaks" with energy $E_{\rm br}$ at 1-10MeV in some large solar energetic particle (SEP) events. Generally, single CME-driven shock applying diffusive acceleration mechanism would just predict a single power-law energy spectrum. This work discusses the difference of the energy spectra between a single shock and the converging double-shock. We apply a single shock and a converging double-shock models to the 2006 Dec 13 SEP event using particle simulation method, respectively. As results, we find that a single shock model just produce an energy spectrum with a single-power law, but a double converging-shock model can produce a "broken" energy spectrum splitting to double power-law, which is consistent with the observed energy spectrum by spacecraft.

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1. Introduction

In an interplanetary (IP) shock, a proton energy spectral “break” (separating two power laws) can be measured by in situ instruments on multiple spacecraft. There are six events with hard energy spectra that occurred on 1997 Nov 6, 2001 Feb 15, 2005 Jan 20, 2005 Sep 7, 2006 Dec 5, and 2006 Dec 13, respectively. These six large events all show their spectral “breaks” in the energy range of $\sim$1-10MeV . In addition, another six of the largest events from the solar cycle 23 list that occurred on 2000 Jul 14, 2000 Nov 8, 2001 Sep 24, 2001 Nov 04, 2001 Nov 22, and 2003 Oct 28, respectively. These events all show spectral “breaks" at about $\sim$50MeV [10]. Here we discuss the 2006 Dec 13 shock event, in which proton fluxes show an energy spectral “break” at $\sim$ 3.5MeV, as measured by spacecraft ACE, STEREO, and SAMPEX.

A number of in-situ observations exhibit the CR’s proton spectral “breaks" associated with interaction between the source and its environment, Desai et al. [3] suggest that double power-law solar energetic particle (SEP) spectra occur due to diffusive acceleration by near-Sun CME shocks rather than scattering in interplanetary turbulence. Here, we suggest that the energy “break” would be associated with the shock interaction regions. So, we try to perform a reliable prediction of the energy spectral “break” using numerical method. Normally, numerical simulation usually builds a simple DSA model with a short size of the diffusive region ahead of the shock. But the energy spectral “break” is usually associated with a large diffusive size, so the energy spectral “break” would hardly be involved in the simulated result. Technically, the hybrid and particle-in-cell(PIC) simulation methods solve the equation explicitly for particle motions in an electromagnetic plasma [6, 7, 16]. PIC and hybrid method can directly model not only the particle acceleration process but the shock formation process as well. Both of them have a great advantage in that they determine the self-generated magnetic turbulence self-consistently, but the extensive energy spectra are not easy to obtain for resolving the issues such as energy spectral “break”. Nevertheless, the Monte Carlo method [4, 12, 11] solves the Boltzman equation using collective scattering technique, replacing of the explicit calculation of the electromagnetic field in the shock region. The scattering mean free path is assumed to be a function of the particle rigidity. Theoretically, this treatment allows to follow the individual ions for a long time and a large size of the diffusive region until the sufficient high energy “tail” presents. Actually, the acceleration efficiency, as well as the maximum particle energy, are dependent on the size of the precursor region, which is parameterized by the size of the free escape boundary (FEB) in the Monte Carlo single shock model. By using a limited computation, Ellison et al. [5] presented an ion spectrum with a maximum particle energy less than 1MeV by applying a fixed FEB size ahead of the bow shock. Knerr et al. [8] and Wang et al. [13] improved the simulated result for the maximum particle energy up to $\sim$4MeV using a moving FEB ahead of the shock. It is still difficult to use a diffusive shock acceleration (DSA) model to solve this energy spectral “break”.

So, in order to testify the IP shock’s energy spectral “break”, we use a single shock model and a double-shock model to follow particle acceleration for producing the energy spectra with the extended energy range beyond the “broken” energy. For all previous works without involving an interaction between shocks, our simulated spectrum did not extend to high enough energies to predict the energy spectral “break”. Firstly, we expect to take an isolated shock as an example to investigate the maximum particle energy and energy spectral “break” by using different values for the scattering time within resonant diffusive scenario, in which the acceleration efficiency is significantly enhanced once the mean free path for particle is approximately equal to the particle gyroradius (i.e. $\lambda \approx r_{\rm L}(E) \propto E/B$), and the diffusion coefficient reads $D_{\rm B}(E) \approx v r_{\rm L}(E)$ [9]. Secondly, we focus on a double-shock interaction (i.e. CME-driven shock interacting with Earth's bow shock)which possibly increases the maximum particle energy. If an enough extensive energy spectrum is available, we will have an opportunity to investigate the energy spectral slope as long as there exists a "broken" energy spectrum, as described in the observed energy spectrum on 2006 December 13.

2. Model

The solar and heliospheric observatory(SOHO) coronagraphs of the halo CME event on 2006 Dec 13 show that CME moved with a speed of 1774kms^{-1}. The fluxes of protons in this solar energetic particle (SEP) event are measured by the ACE, STEREO, and SAMPEX spacecraft in different energy ranges from 0.1MeV to 500MeV. The energy spectral "break" appears at energy ~3.5MeV. We perform a single shock and a double-shock model to obtain the extended energy spectra, which hopefully could cover the energy range from ~0.1MeV to a few decades of MeV. Also we hope to investigate this extended energy spectrum involving a possible energy spectral "break" between 1MeV and 10MeV. In this Monte Carlo method, we apply an initial number density of particles n_0 obeying a Maxwellian distribution with a local thermal velocity $V_{\rm L}$ in the upstream region. Initial particles with their bulk flow speeds of upstream and local thermal velocities ($V = U + V_{\rm L}$) move to the simulation box. The reflective wall at the boundary of the simulation box can be taken as the CME to produce the shock evolving into the simulation box. Then the particles can be scattering with the scatter centers frozen in the upstream and downstream bulk flows. Particles obtain the energy gains for acceleration by multiple crossings on the shock front back and forth (i.e., Fermi acceleration mechanism).

In the isolated shock model, one of the boundary of the simulation box can be taken as the CME for producing a single shock. In this single shock scenario, the maximum particle energy $E_{\rm max}$ will be calculated in different cases by applying different values for the constant of the scattering time. Since the FEB measures the size of the faded turbulent magnetic field in shock precursor region, if the FEB size is larger, then the $E_{\rm max}$ is higher. Since the size of the FEB is larger, the computational expense is higher, we change the scattering time to achieve a higher $E_{\rm max}$ in the shock. Here, we apply the scattering times of τ_0, $\tau_0/2$, $\tau_0/3$, $\tau_0/4$, $\tau_0/5$, and $\tau_0/12.5$ (where, τ_0 is the standard scattering time) in Cases A, B, C, D, E, and F. Assuming a particle can obtain the same additional energy gain from each cycle in a period of the scattering time, it is probable that the more scattering probabilities will obtain the more energy gains. If we take a smaller value for the constant of the scattering time in one simulation case, we can obtain a higher $E_{\rm max}$ value by more scattering probabilities in total simulation time.

In double-shock model, bulk flows are reflected by two walls at the two boundaries of the simulation box and form two downstream regions with high densities of downstream flows. When both two densities of downstream flows reach to their stable states, then two shock fronts evolute smoothly forward to the center of the box with their evolutional velocities $V_{\rm sh1}$ and $V_{\rm sh2}$, respectively. Also when both shock fronts propagate closer and closer, two precursors ahead of their shocks have interactions gradually approximating the center of the simulation box. Interactions of two precursors in converged shocks lead to an amplified magnetic field between two shocks. Particles benefit more energies from this amplified magnetic turbulence in converged two shocks than those in a single shock model. So, the amplified magnetic field could contribute the extensive energy spectrum. However, with the shortening of the precursor regions, less and less particles can obtain more energies from double shocks resulting a soft slope of the high energy spectral "tail". Therefore, the energy spectral "break" would form at a certain energy point between 1-10MeV.

The specific observed parameters and the simulated parameters can be referenced as to the related literatures[12, 13, 11, 14, 15].

3. Results

3.1 Isolated Shock

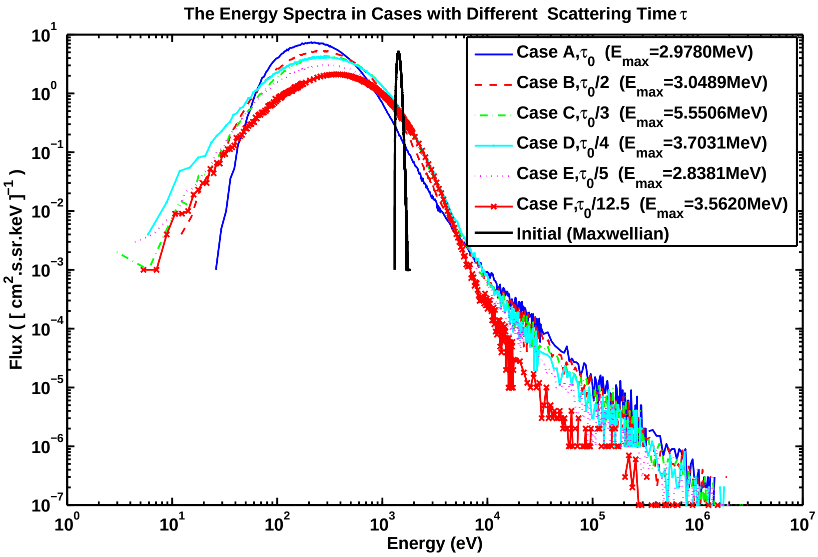

Figure 1: The energy spectra obtained from downstream region in six cases with different values for the scattering time. The thick solid line with a narrow peak at E = 1.43keV represents the initial Maxwellian energy distribution in the upstream region. All of these six cases exhibit the consistent energy spectral slopes at the low energy range and possess maximum particle energies less than 5.5MeV.

Fig.1 shows the shock energy spectra calculated in the downstream region in all cases. As far as the shape of the energy spectrum is concerned, the power-law slope of six extended curves are similar, because all cases are done in the same resonant diffusion scenario just only with different values for the scattering time. However, among these cases, the energy spectrum in Case C with the value for the scattering time of $\tau_0/3$ shows a relatively hard slope in the highest energy spectral tail. Under an isolated shock model, each case shows that how the initial Maxwellian energy spectrum to evolve into the extended energy spectrum with "power-law" structure in its high energy, respectively. By comparison, we calculated the average value of the maximum particle energy in present six cases. The average value for maximum particle energy is $< E_{\max} >$=3.61MeV and the average value for energy spectral index is $\Gamma \sim 1.12$. These results agree with the low energy spectrum in the observations from the multiple spacecraft. Observed energy spectrum[10] shows low energy spectrum with an index of $\Gamma = 1.07$ and a high energy spectrum with an index of $\Gamma = 2.45$. The observed energy spectrum indicates that there exists an $E_{\rm br}$ between the lower energy spectrum and the higher energy spectrum. From these simulated cases, we concluded that all these energy spectra are characterized by a “power-law" with an averaged index $\Gamma \sim 1.12$, which consists with the observed index $\Gamma = 1.07$ of the low energy spectrum. Since there is no maximum particle energy $E_{\rm max}$ in these six cases beyond the upper limit of $E_{\rm br}$ at 10MeV, we are not capable to investigate that there would exist an $E_{\rm br}$ at 1-10MeV as a “break” separating double power laws. If we expect to investigate the double power-law energy spectrum, we can guess that there would exist a magnetic field amplification associated with a double-shock interaction. In the implication from these present simulated results, we propose to build a double-shock model to simulate the $E_{\rm br}$ formation and the higher energy spectrum in the interplanetary shock. In present isolated shock model, we emphasize that the parameter of the scattering time would play key role on the strength of the diffusive coefficient for $E_{\rm max}$ production within the resonant diffusion scenario. According to the simulated results, we find the relationship between the maximum particle energy $E_{\rm max}$ and the different value for the scattering time in isolated shock model. Although there are some lightly differences between these maximum particle energy $E_{\rm max}$ in those simulated cases, no maximum particle energy $E_{\rm max}$ can exceed the upper limit of $E_{\rm br}\sim$10 MeV for failure to predict the “broken” energy spectrum.

3.2 Converging Two Shocks

Fig.2 shows the plot of the simulated proton energy spectrum and the energy spectrum for the event we have studied observed by ACE and STEREO. For convenience, the simulated proton flux is scaled in the same intergrading duration as the observed flux occurred on the period from 2006 Dec 13, 02:00 to Dec 14, 22:00, which is equivalent to 1.584×10^5s. The plot shows a comparison of the simulated energy spectrum and that observed. Each shows a spectral feature in the kinetic energy range from 0.1MeV to 20 MeV. The blue curve represents the observed energy spectrum, which shows the double power-law energy spectrum with a “break” at $\sim$3.5MeV. The lower energy spectrum shows an energy spectral shape with a slope of $E^{-1.07}$, the higher energy spectrum shows a softer energy spectral shape with a slope of $E^{-2.45}$. The red curve represents the simulated energy spectrum, which also shows a spectral “break” at $\sim$5.5MeV indicated by the black vertical dashed-line. The cyan line at the left of the vertical dashed-line represents the lower energy spectrum with an energy slope of $E^{-1.17\pm0.11}$, which exhibits a difference of the fluxes compared with the observed energy spectrum at the lower energy range. The green line and pink line, at the right of the vertical dashed-line, fit the higher energy spectrum with two different energy spectral slopes of $E^{-2.55\pm0.10}$ and $E^{-2.48\pm0.12}$, respectively. At the higher energy range, the pink line with a slope of $E^{-2.48\pm0.12}$ would be more similar to the observed energy spectrum with a slope of $E^{-2.45}$, but it deviates more to the simulated “break” point at the vertical dashed-line. Comparably, the green line with a slope of $E^{-2.55\pm0.10}$ would be more fit for the simulated higher energy spectrum, which possess a smaller deviation to the “break” point at the vertical dashed-line than that of the pink line. The simulated energy spectrum indicated by red curve in Fig.2 is calculated from the downstream regions. The cyan line fits the lower energy spectrum with an index value of $\Gamma_1 = -1.17\pm0.11$. At the higher energy range, the green line fits a suitable energy spectrum with an index value of

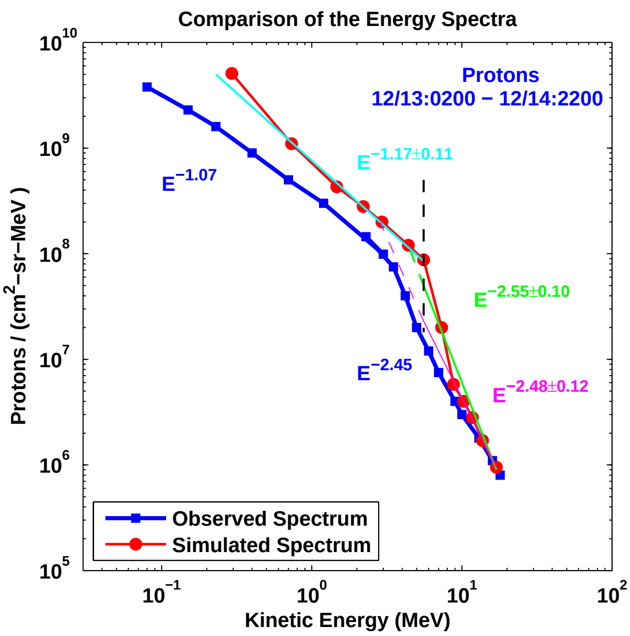

Figure 2: The plot shows the comparison between the simulated proton energy spectrum and the observed one. The red curve represents the simulated energy spectrum, the blue curve represents the observed one. In the simulated energy spectrum, the cyan line represents the lower energy spectrum, the green line and pink line fit the higher energy spectrum with two different indices, respectively. The observed spectrum is analyzed from the data by spacecraft ACE,STEREO-A and STEREO-B. The simulated energy spectrum is scaled in the same integrating duration as the observed energy spectrum.

$\Gamma_{2a} = -2.55 \pm 0.10$. And its extended dashed-line crosses the cyan line over the lower energy range at the point of ∼4.5MeV. The pink line fits the energy spectrum with an index value of $\Gamma_{2b} = -2.48 \pm 0.12$, which would be more close to the observed energy spectral shape over the higher energy range, its extended dashed-line crosses with the cyan line over the lower energy range at the point of ∼3MeV. Although this cross point at ∼3MeV is close to the observed "break" point at ∼3.5MeV, it deviates more to the simulated "break" point at ∼5.5MeV. The observed energy spectrum indicated by blue curve in Fig.2 is analyzed from the proton data by spacecraft ACE/EPAM, STEREO/LET and STEREO/HET [10]. The lower energy spectrum and the higher energy spectrum are "broken" by an energy spectral "break" at the energy point of ∼ 3.5MeV. Generally, the simulated energy spectrum keeps the similar "broken" energy spectral shape with the observed energy spectrum at the energy range from 0.1MeV to 20MeV.

4. Summary and Conclusions

In summary, we simulate an isolated shock model and a converging double-shock model on the 2006 December 13 SEP events. In an isolated shock model, we just obtain an energy spectrum with a single power-law at the lower energy range below 10MeV. We fail to predict the "broken" energy spectrum. In the converging double-shock model, the simulated energy spectrum exhibits a spectral "break" at ∼ 5.5MeV, where the "knee-like" spectral slope changes from a harder to a softer power law. Our simulated spectrum had a maximum energy of a few decades of MeV. With the comparison of the single shock model, we make some of progresses for testifying the particles acceleration and energy spectral features in the interplanetary shocks. So, why do an isolated shock model fail to predict the energy spectral “break” ? There would be some difficulties: (i) According to the diffusive shock acceleration theory, the acceleration efficient is determined by the diffusive coefficient. The attainable highest energy particle is depended on the diffusive length of particles scaled by the size of the precursor region. If we need to allow a single shock simulation to obtain the large extensive energy spectrum, the size of the precursor region should be expanded to be more than hundreds of times of FEB size in current Monte Carlo method. It would be more difficult to perform for the computationally simulation code. (ii) In the term of a single shock, the efficient of the shock kinetic energies translating into the particles is limited. The particles need to travel a long time in their diffusive region for earning energy additions by multiple crossing cycles. So the low injection rate would lead to the difficulty for forming an extended energy spectrum quickly. (iii) Furthermore, in the single shock model, the diffusive particles do not only need long time and large length of the precursor region to achieve an extended energy spectrum, but also this diffusive process would just form a single power-law but not a “broken” power-law energy spectrum.

Here, we explain there are some possibilities for forming an extended energy spectrum and producing a “broken” slope in the converging-shock model. Firstly, the double shocks interaction would provide more kinetic energy injecting into the particles acceleration. The high efficient injection rate excited by amplified magnetic turbulence from the converged region make the extended energy spectrum be possible. Secondly, the double-shock model provide the accelerated particles opportunities to cross the shock more frequently and gain energy faster. With the compressed precursor region, fewer particle’s participate in the acceleration process, leading to a steeper slope at high energy range, resulting in a spectral “break” at about a few MeV. We prove that the shortening precursor region in the converging double-shock model have a negative effect on the accelerated particles. The compressed precursor region lead to a steep spectral slope at the higher energy range. Simultaneously, the amplified magnetic field in the converged region would enhance the energy spectrum extending to a few 10MeV. So, there should be a kind of mechanism to play an important role on forming the amplified magnetic field. We suggest that the non-resonant hybrid instabilities (NRH) would contribute the amplified magnetic field in the shortening converged region [1, 2].

References

[1] A. R. Bell, 2013, *Astroparticles Physics*, **43**, 56-70

[2] A. M. Bykov, & R. A. Treumann, 2011, *Astron. Astrophys. Rev.,* **19**, 42.

[3] M. I. Desai, G. M. Mason, M. A. Dayeh, et al. 2016, *ApJ*, **828**, 106-124.

[4] D. C. Ellison, & D. Eichler, 1984, *ApJ*, **286**, 691

[5] D. C. Ellison, E. Möbius, & G. Paschmann,1990, *ApJ*, **352**, 376-394

[6] J. Giacalone, D. Burgess, S. J. Schwartz, & D. C. Ellison, 1993, *ApJ*, **402**, 550-559

[7] F. Guo, & J. Giacalone,2013, *ApJ*, **773**, 158

[8] J. M. Knerr, J. R. Jokipii, & D. C. Ellison, 1996, *ApJ*, **458**, 641-652

[9] P. O. Lagage, C. J. Cesarsky, 1983, *Astron. Astrophys.*, **125**, 249

[10] R. A. Mewaldt, C. M. S. Cohen, A. C. Cummings, et al. 2008, in proceedings of *the 30th ICRC(Mexico)*, **1**, 107-110.

[11] X. Wang, N. Wang, & Y. H. Yan, 2013, *ApJS*, **209**, 18

[12] X. Wang, & Y. H. Yan, 2011, *Astron. Astrophys.*, **530**, A92

[13] X. Wang, & Y. H. Yan, 2012, *Res. Astron. Astrophys.*, **12**, 1535-1548

[14] X. Wang, Y. H. Yan, M. D. Ding, N. Wang, & H. Shan, 2016, *Res. Astron. Astrophys.*, **16**, 32

[15] X. Wang, J. Giacalone, Y. H. Yan, M. D. Ding, N. Wang, & H. Shan,2017, *ApJ*, **842**, 74

[16] Z. Yang, Y. D. Liu, J. D. Richardson, et al, 2015, *ApJ*, **809**, 28