Particle Acceleration at High-\(\gamma\) Shock Waves

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Abstract. First-order Fermi acceleration processes at ultrarelativistic (\(\gamma \approx 5-30\)) shocks are studied with the method of Monte Carlo simulations. The accelerated particle spectra are obtained by integrating the exact particle trajectories in a turbulent magnetic field near the shock. The magnetic field model assumes finite-amplitude perturbations within a wide wavevector range and with a predefined wave power spectrum, which are imposed on the mean field component inclined at some angle to the shock normal. The downstream field structure is obtained as the compressed upstream field. We show that the main acceleration process at oblique shocks is the particle compression at the shock. Formation of energetic spectral tails is possible in a limited energy range for highly perturbed magnetic fields. Cut-offs in the spectra occur at low energies in the resonance range considered. We relate this feature to the structure of the magnetic field downstream of the shock, where field compression produces effectively 2D turbulence in which cross-field diffusion is very small. Because of the field compression downstream, the acceleration process is inefficient also in parallel high-\(\gamma\) shocks for larger turbulence amplitudes, and features observed in oblique shocks are recovered. For small-amplitude perturbations, particle spectra are formed in a wide energy range and modifications of the acceleration process due to the existence of long-wave perturbations are observed. The critical turbulence amplitude for efficient acceleration at parallel shocks decreases with \(\gamma\). We also study the influence of strong short-wave perturbations, generated downstream of the shock, on the particle acceleration processes at high-\(\gamma\) shocks. The spectral indices obtained do not converge to the “universal” value \(\alpha = 2\). Our results indicate inefficiency of the first-order Fermi process to generate high-energy cosmic rays at ultrarelativistic shocks with the perturbed magnetic field structures considered in the present work.

Keywords: acceleration of particles, cosmic rays, shock waves, numerical methods

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In the present work we investigate the first-order Fermi process at relativistic shocks in test-particle approach with the method of Monte Carlo simulations. The applied magnetic field model includes the characteristic features essential for a realistic description of the acceleration process. The upstream magnetic field consists of the uniform component \(B_0\), inclined at some angle \(\psi\) to the shock normal, and static finite-amplitude perturbations imposed upon it. The irregular component has either a flat \(F(k) \sim k^{-1}\) or a Kolmogorov \(F(k) \sim k^{-5/3}\) wave power spectrum defined in a wide wavevector range with \(k_{\text{max}} = k_{\text{min}} = 10^5\). The downstream field structure is obtained as the compressed upstream field, so that the continuity of the turbulent magnetic field across the shock is preserved. This allows one to study correlations in particle motion introduced by the field structure for different levels of turbulence, and to investigate their influence on the particle spectra. Furthermore, the magnetic field model enables one to discuss the role of long-wave magnetic field perturbations. The details of the model and earlier results for acceleration at mildly relativistic shocks have been described elsewhere [1]. Here, we apply the model to investigate particle acceleration at high-\(\gamma\) shocks (see also [2]).
FIGURE 1. Accelerated particle spectra at oblique ($\psi_1 = 45^o$) superluminal shock waves in the shock normal rest frame. The shock is assumed to be a planar discontinuity, propagating with Lorentz factor $\gamma_1$ with respect to the upstream (electron-proton) plasma. Figure 1a shows particle spectra for $\gamma_1 = 5$ and a flat power spectrum of magnetic field perturbations for different upstream perturbation amplitudes $\delta B = B_0 \delta$. Spectra have vertical shifts for clarity. Particle spectra obtained for different $\gamma_1$ and the Kolmogorov wave power spectrum with $\delta B = B_0 \delta = 1$ are presented in Fig. 1b. Particles in the range $(2\pi/k_{max}, 2\pi/k_{min})$ can satisfy the resonance condition $k_{res} \sim 2\pi r_g (E)$.

The particle spectra are obtained by following exact particle trajectories in the perturbed magnetic field near the shock, without the simplifying hybrid approach used in [1].

The characteristic features of particle acceleration processes at oblique superluminal high-$\gamma$ shocks are illustrated in Fig. 1. All injected particles are initially accelerated in a phase of “superadiabatic” compression at the shock [3]. Only a much smaller fraction of these particles is further accelerated in the first-order Fermi process, forming an energetic tail in the spectrum for highly perturbed magnetic fields. The shape of the spectral tail and its extension to high particle energies strongly depend on the magnetic field turbulence spectrum. For the flat wave power spectrum, the tails are very steep (Fig. 1a), whereas for the Kolmogorov turbulence, with most power in long-wave perturbations, they are much flatter and exhibit a continuous slow steepening (Fig. 1b). Cut-offs appearing in the spectra occur in the resonance energy range considered, and the cut-off energy decreases with growing shock Lorentz factor $\gamma_1$ (Fig. 1b).

The features observed in the spectra can be explained by the turbulent magnetic field structure at the shock. The field compression downstream of the shock produces effectively 2D turbulence in which particle diffusion conditions are highly anisotropic, with very limited diffusion along the shock normal. This leads to high particle escape rates and results in steep particle spectra, as seen in Fig. 1a. Flatter particle spectra for the Kolmogorov turbulence (Fig. 1b) result from the effects of high-amplitude long-wave magnetic field perturbations which can form locally subluminal field configurations at the shock, thus enabling more efficient particle-shock interactions. Increasing $\gamma_1$ leads to a decrease in the particle cross-field diffusion downstream of the shock, which is the most important factor leading to the lowering of the cut-off energy, as seen in Fig. 1b.

The effects of downstream magnetic field compression may also occur in parallel
FIGURE 2. Accelerated particle spectra at ultrarelativistic shocks with $\gamma_1 = 10$ formed in the presence of small-scale large-amplitude perturbations generated downstream of the shock. The wave power spectrum of the compressed magnetic field component is flat ($F(k) \sim k^{-1}$) upstream of the shock. Particle spectra at superluminal shocks ($\psi_1 = 45^\circ$) and $\delta B/B_0,1 = 1$ are shown in Fig. 2a, and spectra at parallel shocks ($\psi_1 = 0^\circ$) and $\delta B/B_0,1 = 0$ are presented in Fig. 2b. Energy density in the short-wave component relative to the energy density in the compressed downstream magnetic field $\delta B_{sh} = < B_2 >$ is given near the respective results. Linear fits to the spectra are presented and values of the (phase-space) spectral indices $\alpha$ are given in italic (the energy spectral index $\sigma = \alpha / 2$). The spectra shown with solid line are obtained in the model without small-scale perturbations. Spectrum shown with diamonds in Fig. 2b represents the model with particle pitch-angle scattering upstream of the shock, which does not include the effects of long-wave magnetic field perturbations.

high-$\gamma$ shocks. In the case of large-amplitude perturbations, the field compression leads to the effectively perpendicular shock configuration. The acceleration processes thus become less efficient and features analogous to those observed in superluminal shocks are recovered. In conditions of weakly perturbed magnetic fields, wide-energy range particle spectra are formed. They are non-power-law in the entire energy range, and their power-law parts are flat ($\alpha < 4$) due to the presence of long-wave perturbations, as reported previously for mildly relativistic shocks [1]. The critical turbulence amplitude for efficient acceleration at parallel shocks decreases with $\gamma_1$. This character of the acceleration process deviates from the results of the classical models, e.g., [4-6], which suggest the existence of a “universal” spectral index $\alpha = 4.2$ for ultrarelativistic shocks.

We also study the effects of an additional highly nonlinear short-wave turbulence generated downstream of the shock due to, e.g., the Weibel instability [7-9]. We assume that these short-wave perturbations form isotropic 3D turbulence, which provides efficient particle scattering and may lead to a decorrelation between particle motion and the compressed field downstream of the shock. The influence of such perturbations on particle trajectories is included as a small-amplitude momentum scattering term, as in the hybrid method described in [1] (see also [10]).

Particle spectra formed in the presence of the short-wave turbulence downstream of the superluminal shock with $\gamma_1 = 10$ are shown in Fig. 2a. Efficient particle acceleration is possible if the energy density in the short-wave component is much higher than the...
mean energy density in the compressed downstream magnetic field. In such conditions, particle spectra with (steep) power-law parts can be formed, and the spectral index does not depend on $\delta B_{sh} = < B_2 >$ above some critical value. Cut-offs in the spectra occur because the efficiency of particle scattering due to small-scale perturbations diminishes with particle energy. This means that $\delta B_{sh} = < B_2 >$ must be extremely large to decorrelate the motion of high-energy particles from the compressed downstream field and produce power-law spectra in the full energy range. Accelerated particle spectra formed at parallel shocks with $\gamma_1 = 10$ are shown in Fig. 2b. Note that the particle spectral index deviates from the “universal” value $\alpha = 4.2$, even in the limit of $\delta B_{sh} = < B_2 >$. Only in the model with pitch-angle scattering upstream of the shock, which does not include the effects of long-wave perturbations, the “universal” spectral index is observed.

Our results require a revision of many earlier discussions of cosmic ray acceleration up to very high energies in the first-order Fermi process at ultrarelativistic shocks. The modeling shows that for the analyzed turbulent magnetic field structures near the shocks, which are consistent with the shock jump conditions, it is difficult to form wide-energy power-law particle spectra in quasi-perpendicular (superluminal) and also parallel high-$\gamma$ shocks. This substantially modifies the shock acceleration picture of classical models which predict power-law spectra, often with the “universal” spectral index. The presence of highly nonlinear short-wave turbulence at the shock can lead to more efficient acceleration, but the energy density in the small-scale component required to do so may be unrealistically high, in particular for large $\gamma_1$. The formation of a spectrum with “universal” index requires special conditions, which include strong particle scattering both downstream and upstream of the shock. This suggests possibly different mechanism for particle acceleration to very high energies, e.g., [11]. However, a detailed knowledge of the magnetic field structure near a relativistic shock is needed to reach definite conclusions as to the effectiveness of particle acceleration.

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