Cosmic ray acceleration at parallel relativistic shocks in the presence of finite-amplitude magnetic field perturbations

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Abstract

We study the first-order Fermi acceleration process at parallel shock waves by means of Monte Carlo simulations. A 'realistic' model of the magnetic field turbulence is applied involving sinusoidal waves imposed on the background mean field parallel to the shock normal. The finite-amplitude magnetic field perturbations lead to locally oblique field configurations at the shock and the respective magnetic field compression. It results in modification of the particle acceleration process introducing some features observed in oblique shocks, e.g. particle reflections from the shock. For the parallel mildly relativistic shocks we demonstrate for the first time a (non-monotonic) variation of the accelerated particle spectral index with the turbulence amplitude.

1. Introduction

As discussed by Ostrowski [9] for nonrelativistic shocks, the presence of finite-amplitude magnetic field perturbations modify character of the diffusive particle acceleration at the shock wave with the mean field parallel to the shock normal. The effect arises due to locally oblique field configurations formed by long-wave perturbations at the shock front and the respective magnetic field compressions. As a result the mean particle energy gains may increase and the particles reflected from the shock front may occur. The same phenomena should occur at relativistic shocks [cf. 10].

In the simplified numerical simulations of the first-order Fermi acceleration at parallel mildly relativistic shocks the acceleration time scale reduces with increasing turbulence level, but no spectral index variation occurs [1, see 2 for ultrarelativistic shocks]. However, the considered acceleration models apply very simple modeling of the perturbed magnetic field effects by introducing particle pitch-angle scattering. The purpose of the present work is to simulate the first-order Fermi acceleration process at mildly relativistic shock waves propagating in more realistic perturbed magnetic fields, including a wide wave vector range turbulence with the power-law spectrum. The magnetic field is continuous across

pp. 2019–2022

the shock, according to the respective jump conditions. This feature leads to substantial modifications of the acceleration process at parallel shocks.

Below the upstream (downstream) quantities are labeled with the index '1' ('2').

2. Simulations

In the simulations trajectories of ultrarelativistic test particles are derived by integrating their equations of motion in the perturbed magnetic field [for details see: Niemiec, Ostrowski, in preparation]. A relativistic shock wave is modeled as a plane discontinuity propagating in electron-proton plasma. The magnetic field is defined upstream of the shock. It consists of the uniform component, $\vec{B}_{0,1}$, parallel to the shock normal and finite-amplitude perturbations imposed upon it. The perturbations are modeled as a superposition of 294 sinusoidal static waves of finite amplitudes [cf. 10]. They have either a flat ($F(k) \sim k^{-1}$) or a Kolmogorov ($F(k) \sim k^{-5/3}$) wave power spectrum in the (wide) wave vector range (k_{min}, k_{max}), where $k_{max}/k_{min} = 10^5$. The shock moves with the velocity u_1 with respect to the upstream plasma. The downstream flow velocity u_2 and the magnetic field structure are obtained from the hydrodynamic shock jump conditions. Derivation of the shock compression ratio as measured in the shock rest frame, $R = u_1/u_2$, is based on the approximate formulae derived in Ref. [3]. In the analysis of the acceleration process the particle radiative (or other) losses are neglected.

3. Results for parallel shocks

In Fig. 1 we present particle spectra for the parallel shock wave with $u_1 = 0.5c$. The shock compression ratio is $R = 5.11$. The particle spectra are measured at the shock for three different magnetic field perturbation amplitudes and the flat (Fig. 1a) or the Kolmogorov (Fig. 1b) wave power spectrum. One can note that the particle spectral indices deviate from the small amplitude results of the pitch angle scattering model [3-6]. In addition, the increasing magnetic field perturbations can produce non-monotonic changes of the particle spectral index – the feature which has not been discussed for parallel shocks so far. Analogously to oblique shock waves [cf. an accompanying paper in this volume], our particle spectra are non power-law in the full energy range and the shape of the spectrum vary with the amplitude of turbulence and the wave power index.

The non-monotonic variation of the spectral index with the turbulence amplitude results from modifications of the particle acceleration process at the shock. The long-wave finite-amplitude perturbations produce locally oblique mag-

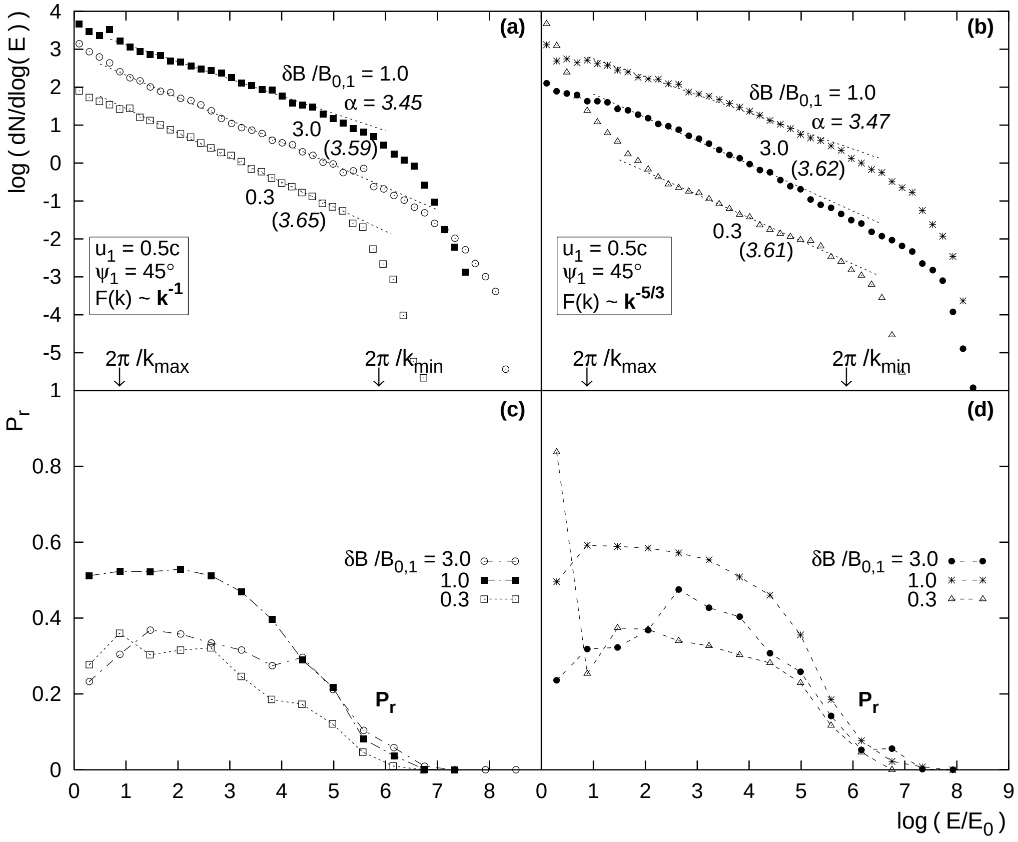

Fig. 1. Accelerated particle spectra at the parallel shock wave in the shock rest frame for (a) the flat ($F(k) \propto k^{-1}$) and (b) the Kolmogorov ($F(k) \propto k^{-5/3}$) wave spectrum of magnetic field perturbations. The upstream perturbation amplitude $\delta B/B_{0,1}$ is given near the respective results. Linear fits to the power-law parts of the spectra are presented and values of the phase space distribution function spectral indices α are given in parentheses. Particles in the energy range indicated by arrows can effectively interact with the magnetic field inhomogeneities ($k_{min} < k_{res} < k_{max}$). For upstream particles probabilities of reflection from the shock, P_r, are presented as a function of particle energy for the respective particle spectra above (the transmission probability $P_{12} = 1 - P_r$).

netic field configurations and lead to occurrence of particles reflected from the compressed field downstream of the shock. Probability of reflection depends on the turbulence amplitude and the amount of field perturbations with wavelengths larger than the resonance wavelength for a given particle, as presented in Figs. 1c and 1d. For $\delta B/B_{0,1} = 1.0$ the reflection probability is higher as compared to the other perturbation amplitudes considered and the particle spectrum is flatter. For the chosen by us smaller ($\delta B/B_{0,1} = 0.3$) and larger ($\delta B/B_{0,1} = 3.0$) turbulence amplitudes the reflection and transmission probability do not differ considerably, which results in the similar values of the spectral indices. One can note in this place, that the obtained spectra for the Kolmogorov case seem to exhibit a continuous slow change of inclinations. Thus the fitted power-laws depend to some extent on the energy range chosen for the fit. One can also note a steep part of the spectrum at low energies for $\delta B/B_{0,1} = 0.3$ in Fig. 1b.

The presented reflection (transmission) probabilities decrease (increase) at high particle energies due to a limited dynamic range of the magnetic field turbulence. The locally oblique field configurations are mainly formed by long-wave perturbations ($k < k_{res}$) [cf. 9]. For high energy particles with $k_{res} < k_{min}$ there are no respectively long waves and the upstream particles can be only transmitted downstream of the shock. In these conditions the acceleration process would converge to the 'classic' parallel shock acceleration model, but in our simulations particles move far to the introduced escape boundary forming a cut-off.

4. Summary

The simulations of the first-order Fermi acceleration process acting at parallel relativistic shock waves are presented. In the presence of finite-amplitude perturbations the particle spectral indices vary in a non-monotonic way with the turbulence amplitude due to non trivial character of the particle interaction with the shock, including particle reflections. This feature is also expected to lead to some decrease of the particle acceleration timescale in comparison to previous estimates [7, cf. 8].

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References

1. Bednarz J., Ostrowski M. 1996, MNRAS 283, 447
2. Bednarz J., Ostrowski M. 1998, Phys. Rev.Lett. 80, 3911
3. Heavens A., Drury L'O.C. 1988, MNRAS 235, 997
4. Kirk J.G., Heavens A. 1989, MNRAS 239, 995
5. Kirk J.G., Schneider P. 1987, ApJ 315, 425
6. Kirk J.G., Schneider P. 1987, ApJ 322, 256
7. Lagage P.0., Cesarsky C.J. 1983, A&Ap 118, 223
8. Ostrowski M. 1988, MNRAS 233, 257
9. Ostrowski M. 1988, A&Ap 206, 169
10. Ostrowski M. 1993, MNRAS 264, 248