Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 2 (OG part 1), pages 283–286

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

The inefficiency of the first-order Fermi process in UHECR production at relativistic shocks

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Abstract: The question of the origin of ultra-high-energy cosmic rays at relativistic shock waves is discussed in the light of results of recent Monte Carlo studies of the first-order Fermi particle acceleration [1, 2]. The models of the turbulent magnetic field near the shock considered in these simulations include realistic features of the perturbed magnetic field structures at the shock, which allow us to study all the field and particle motion characteristics that are important for cosmic-ray acceleration. Our results show that turbulent conditions near the shock, that are consistent with the shock jump conditions, lead to substantial modifications of the acceleration process with respect to the simplified models, that produce wide-range power-law energy distributions, often with the "universal" spectral index. Relativistic shocks are essentially always superluminal, and thus they preferentially generate steep particle spectra with cutoffs well below the maximum scattering energy, often not exceeding the energy of the compressed background plasma ions. Thus, cosmic-ray acceleration to very high energies at relativistic shock waves is inefficient, and such shocks are not expected to be the sources of ultra-high-energy particles.

Introduction

Relativistic shocks are widely considered to generate energetic particle populations (cosmic rays) responsible for the high-energy emission of astrophysical sources such as hot spots in radio galaxies, quasar jets and gamma-ray burst afterglows. The basic acceleration mechanism discussed in this context is the first-order Fermi process. It is believed that the Fermi process is intrinsically efficient and thus also capable of the production of ultra-high-energy particles. In this work we confront this opinion and show that the generation of UHECRs at relativistic shocks must invoke processes other that the first-order Fermi mechanism.

Numerical models and results

Modeling of first-order Fermi acceleration at relativistic shocks is a difficult task because cosmic-ray distributions are highly anisotropic at the shock and the resulting particle spectra depend strongly on the essentially unknown local conditions at the shocks. In the series of our recent studies of the Fermi process [3, 1, 2] we have to considered the most realistic models possible for the perturbed magnetic field structures at the shock, which allow us to study all the field characteristics important for particle acceleration. The upstream magnetic field is assumed to consist of the uniform component $\boldsymbol{B}_{0,1}$, inclined at an angle ψ_1 to the shock normal[1], 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 $k_{max}/k_{min} = 10^5$, which allows us to investigate the role of the long-wave turbulence in the acceleration process. The downstream field structure is obtained as the compressed upstream field, so that the magnetic field lines are continuous across the shock. This allows one to study upstream-downstream correlations in particle motion introduced by the field structure for different levels of turbulence, and to investigate the

1. Indices "1" and "2" refer to quantities in the upstream and downstream plasma rest frame, respectively.

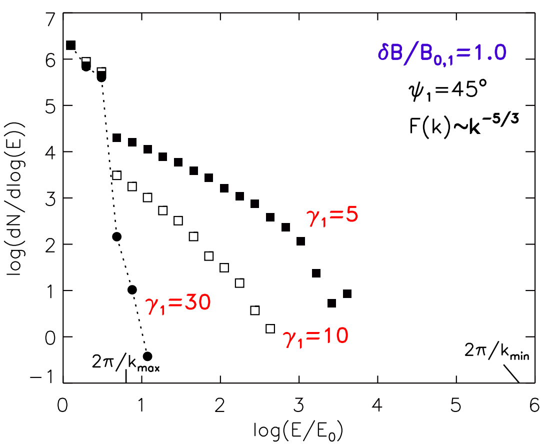

Figure 1: Accelerated particle spectra in the shock rest frame at oblique ($\psi_1 = 45^o$) superluminal shock waves for different shock Lorentz factors γ_1. The Kolmogorov wave power spectrum is assumed for the turbulent magnetic field, and the upstream perturbation amplitude $\delta B/B_{0,1} = 1.0$. Particles in the range ($2\pi/k_{max}$, $2\pi/k_{min}$) can satisfy the resonance condition $k_{res} \simeq 2\pi/r_g(E)$ for some of the waves in the turbulence spectrum.

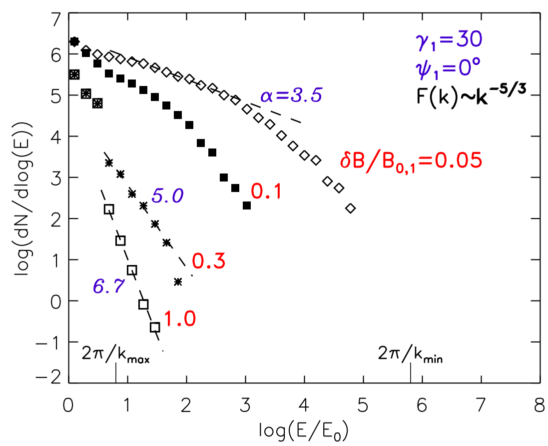

Figure 2: Particle spectra at parallel shock waves with γ_1=30 for different amplitudes of the magnetic field perturbations $\delta B/B_{0,1}$. Linear fits to the spectra are presented and values of the (phase-space) spectral indices α are given in italic (the energy spectral index $\sigma = \alpha - 2$). Some spectra are vertically shifted for clarity.

influence of this factor on particle spectra. We study the first-order Fermi process in *test-particle* approach with the method of Monte Carlo simulations, which calculates the particle spectra by following exact particle trajectories in the perturbed magnetic field near the shock. A shock has a planar geometry and propagates with Lorentz factor γ_1 with respect to the upstream plasma.

Because nearly all magnetic field configurations in relativistic shocks lead to a perpendicular (superluminal) shock structure, the characteristic features of particle acceleration processes at high-γ shocks are best illustrated using the oblique shock example of Fig. 1. All injected particles are initially accelerated in a phase of "superadiabatic" compression at the shock [4]. 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. The tails for the Kolmogorov turbulence (Fig. 1), with most power in long-wave perturbations, are much flatter than for the flat wave power spectrum. However, in either case, the spectra steepen and/or the energy cut-offs occur in the resonance energy range, and the cut-off energy decreases with growing shock Lorentz factor. These spectral features result from the character of particle transport in the magnetic field downstream of the shock, where field compression produces effectively 2D turbulence, in which particle diffusion along the shock normal is strongly suppressed. In effect, advection of particles with the downstream flow leads to high particle escape rates, resulting in steep particle spectra. The existence of the Kolmogorov turbulence at the shock allows for the formation of more extended and flatter spectral components, due to 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. However, the importance of these effects diminishes for larger shock Lorentz factors.

The effects of the turbulent field compression may also occur in parallel high-γ shocks (Fig. 2) for large-amplitude perturbations. In this case, the field compression leads to an effectively perpendicular shock configuration, and features analo-

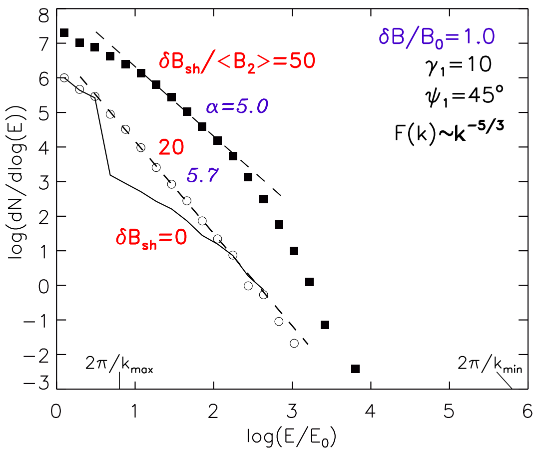

Figure 3: Particle spectra for superluminal shocks with γ_1=10 formed in the presence of shock-generated downstream turbulence and the Kolmogorov power spectrum of the background field component (solid line — compare Fig. 1). The amplitudes of the short-wave perturbations, $\delta B_{sh}/\langle B_2\rangle$, are given near the respective spectra.

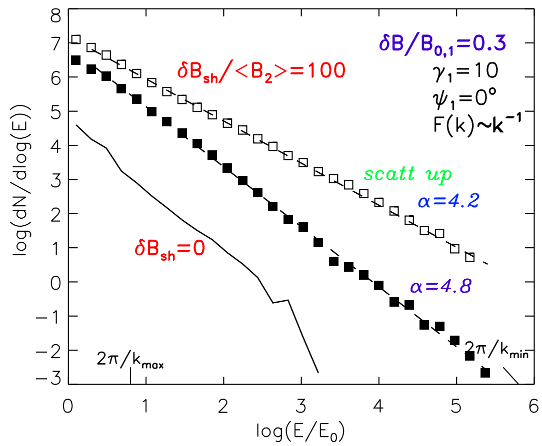

Figure 4: Accelerated particle spectra at parallel shocks with γ_1=10 in the presence of shock-generated turbulence and weakly perturbed background field. The spectrum indicated as "*scatt up*" was obtained in the *unphysical* model in, which the particle pitch-angle diffusion was assumed to exist both downstream and upstream of the shock.

gous to those observed in oblique shocks are recovered. Only for weakly perturbed magnetic fields can the wide-energy range particle spectra be formed. However, they are non-power-law in the full energy range, and their power-law parts are flat ($\alpha < 4$) due to the effects of long-wave perturbations. The convergence of the spectra to the "universal" spectral index ($\alpha \approx 4.2$) claimed in the literature [e.g., 1, 3, 4] is clearly not observed.

More realistic microscopic models of collisionless shocks show that the shocks can generate a highly nonlinear *short-wave* turbulence downstream due to filamentation instabilities at the shock front [5, e.g.]. In [2] we augmented the magnetic field model by this shock-generated component, which can provide efficient particle scattering and may lead to a decorrelation between particle motion and the compressed field downstream of the shock. For the case of oblique shocks (Fig. 3), increasing the amplitude of the shock-generated turbulence leads to a more efficient acceleration with particle spectral tails extending to higher energies. However, in all cases, in which $\delta B_{sh}/\langle B_2\rangle \gg 1$, the energetic spectral tails are convex, and the spectra have cutoffs at energies for which the resonance condition for interactions with compressed turbulence is fulfilled. This is because the influence on particle trajectories of the shock-generated turbulence decreases with increasing particle energy, and eventually becomes smaller than the influence of the large-scale background field. Similar spectral effects are also observed for parallel shocks when the amplitude of the long-wave background component is large. Extended power-law particle distributions can be formed in parallel shocks propagating in a medium with low-amplitude of the long-wave turbulence (Fig. 4). However, the spectra are steeper than the expected "universal" spectrum, $\alpha > \alpha_u$. The only case in which we were able to obtain spectra with $\alpha = \alpha_u$ in the energy range considered, involved the *unphysical* model with the short-wave component introduced both downstream and *upstream* of the shock (spectrum indicated as "*scatt up*" in Fig. 4), which removed the effects of upstream long-wave perturbations.

Discussion and conclusions

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 relativistic shocks. The modeling shows that turbulence consistent with the shock jump conditions can lead to a substantial modifications of the acceleration picture as compared to simplified models producing wide-range power-law energy distributions, often with the "universal" spectral index [6, 7, 8]. The presence of highly nonlinear short-wave turbulence at the shock can lead to more efficient acceleration, but the amplitude of the shock-generated component required to produce extended power-law spectra is unrealistically high, in particular for large shock Lorentz factors. Our simulations show that relativistic shocks, being essentially always superluminal, possibly generate accelerated particle distributions with cutoffs below either the maximum resonance energy enabled by the *high-amplitude* background turbulence ($r_g(E_{cutoff}) < \lambda(E_{res,max})$), or approximately at the energy of the compressed background plasma ions $E_{cutoff} \sim \gamma_1 m_i c^2$. Thus, in conclusion, relativistic shocks are not promising sites as possible sources of ultra–high-energy cosmic rays. Should UHECR production be expected from relativistic shocks it must invoke other processes, e.g. the second-order Fermi process in downstream relativistic MHD turbulence [9].

Finally let us note that our models might have recently acquired observational confirmation. The recent *Spitzer* imaging of Cygnus A hotspots resulted in the detection of the high-energy tails of their synchrotron radiation [10]. Combined with data collected at other frequencies, these observations allowed for a detailed modeling of the broadband emission from the two brightest hotspots, which put precise constraints on the underlying energy spectra of ultrarelativistic electrons. The spectra can be approximated by a broken power-law with the flat low-energy spectral index $\alpha_l \approx 3.5$ followed by a steep high-energy part with $\alpha_h > 5$, with the break energy corresponding approximately to the proton rest mass energy. Thus, the shape of the spectra reflects most likely two different regimes of the electron acceleration process at mildly relativistic shocks of the hotspots: the preacceleration processes responsible for the spectral shape below the critical energy scale given by the inertia of protons, above which the first-order Fermi process operates. The steep slope of the spectra at high-energies is therefore in agreement with our modeling of the Fermi processes at oblique mildly relativistic shocks. In fact, the differences in the high-energy power-law indices and cut-off energies observed between the two hotspots may be attributed to the sensitivity of the Fermi process to the measured differences in the intensity (and possibly configuration) of the magnetic field at the shocks in the hotspots.

This work was supported by MNiSW in years 2005-2008 as a research project 1 P03D 003 29.

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