Gamma-Ray Burst Prompt Emission: 
Implications from Shock Acceleration Theory

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Abstract

The principal paradigm for gamma-ray bursts suggest that the prompt transient gamma-ray signal arises from multiple shocks internal to the relativistic expansion. This paper illustrates some properties of diffusive acceleration at relativistic shocks that pertain to GRB models, providing interpretation of the BATSE/EGRET data. Using a standard Monte Carlo simulation, computations of the spectral shape, and the range of spectral indices are presented, as functions of the shock speed, magnetic field obliquity and the type of particle scattering. It is clear that while quasi-parallel, relativistic shocks with fields approximately normal to the shock plane can efficiently accelerate particles, highly oblique and perpendicular ones cannot unless the particle diffusion is almost isotropic, i.e. extremely close to the Bohm limit. Accordingly, an array of distribution indices should be present in the burst population, as is exhibited by the EGRET data, and even mildly-relativistic internal shocks require strong field turbulence in order to model the > 100 MeV observations. In addition, recent spectral fitting to burst data in the BATSE band is discussed, providing probes of the efficiency of injection of non-thermal electrons.

Key words: Gamma-Ray Bursts, Compton Gamma-Ray Observatory, Relativistic Shocks, Particle Acceleration, MHD outflows

1 Introduction

Gamma-ray bursts are among the most interesting and exotic phenomena in astrophysics. In standard gamma-ray burst (GRB) models, the rapidly expanding fireball cools, converting the internal energy of the hot plasma into kinetic energy of the beamed, relativistically moving ejecta and electron-positron pairs. At the point where the fireball becomes optically thin and the GRB we
see is emitted, the matter is too cool to emit gamma-rays unless some mechanism can efficiently re-convert the kinetic energy back into internal energy, i.e., unless some particle acceleration process takes place. Diffusive shock (Fermi) acceleration is widely believed to be this mechanism (e.g., Rees & Mészáros 1992; Piran 1999). The large energy release in radiation from GRBs, coupled to the limits on available energy from likely sources such as supernovae or coalescing compact objects (see Piran 1999 and Mészáros 2002 for reviews), requires that this acceleration of particles at shocks be efficient. Moreover, the rapid variability of the prompt emission together with the impressive power of these sources strongly suggests that their environs are moving ultrarelativistically (e.g. Paczyński 1986), an indication reinforced by inferences from γγ transparency arguments (e.g. Baring & Harding 1997). Therefore, a detailed understanding of particle acceleration at relativistic shocks is clearly motivated for GRB studies.

Acceleration of particles at non-relativistic shocks has been extensively investigated in the contexts of supernova remnant and heliospheric shocks. Diffusive acceleration at relativistic shocks is less exhaustively studied than that for non-relativistic flows, yet it may occur in extreme objects such as pulsar winds, hot spots in radio galaxies, jets in active galactic nuclei and micro-quasars, and GRBs. Early work on relativistic shocks was mostly analytical in the test-particle approximation (e.g., Peacock 1981; Kirk & Schneider 1987a; Heavens & Drury 1988; Kirk & Webb 1988). Some analytic work (Schneider & Kirk 1987; Baring & Kirk 1991) has explored nonlinear, cosmic ray modified shocks. Complementary Monte Carlo techniques have been employed for relativistic shocks by a number of authors, including test-particle analyses by Kirk & Schneider 1987b and Ellison, Jones & Reynolds (1990) for parallel, steady-state shocks, and extensions to include oblique magnetic fields by Ostrowski (1991), Ballard & Heavens (1992) and Bednarz & Ostrowski (1998).

A key characteristic that distinguishes relativistic shocks from their non-relativistic counterparts is their inherent anisotropy due to rapid convection of particles through and away downstream of the shock, since particle speeds \( v \) are never much greater than the downstream flow speed \( u_2 \sim c/3 \). Accordingly, the diffusion approximation, the starting point for virtually all analytic descriptions of acceleration at non-relativistic shocks, cannot be invoked since it requires nearly isotropic distribution functions. Hence analytic approaches prove more difficult for relativistic shocks, though advances in special cases such as the limit of extremely small angle scattering (pitch angle diffusion) are possible (Kirk & Schneider 1987a; Kirk, et al. 2000; Keshet & Waxman 2004). This paper explores some of the distinctive properties of particle acceleration at relativistic shocks that are germane to the gamma-ray burst paradigm, with a focus on spectral issues, specifically the slope of the power-law distribution and the efficiency of generation of this non-thermal component.
A most attractive feature of non-relativistic shock acceleration theory is that the distribution of accelerated particles is scale-independent, i.e., a power-law. This is a consequence of high energy particles (those with speeds \( v \gg u_1 \), with \( u_1 \) being the upstream flow speed) attaining isotropy in all pertinent reference frames. At such energies, the principal transport equation describing the acceleration process, the diffusion-convection equation, can be solved analytically for plane shocks (e.g., Blandford & Ostriker 1978; Jones & Ellison 1991), yielding the well-known result for the momentum distribution

\[
\frac{dn}{dp} \propto p^{-\sigma} \quad \text{with} \quad \sigma = \frac{r + 2}{r - 1},
\]

where \( r = u_1/u_2 \) is the shock (velocity) compression ratio, \( p \) is the momentum. Eq. (1) is a steady-state, test-particle result, and the index \( \sigma \) depends only on the velocity compression ratio \( r \), i.e., hydrodynamic quantities. This elegant result does not carry over to relativistic shocks because of their strong plasma anisotropy. As a consequence, while power-laws are in fact created, the index \( \sigma \) becomes a function of the flow speed, the field obliquity, and the nature of the scattering, all of which intimately control the degree of particle anisotropy.

In the specific case of parallel (i.e., those where the field is locally normal to the shock surface), ultrarelativistic shocks, the analytic work of Kirk et al. (2000) demonstrated that as \( \Gamma_1 = 1/\sqrt{1 - (u_1/c)^2} \to \infty \), the spectral index \( \sigma \) asymptotically approached a constant, \( \sigma \to 2.23 \) (see also Keshet & Waxman 2004), a value realized once \( \Gamma_1 \gtrsim 10 \). This captivating result has been confirmed by Monte Carlo simulations (Bednarz & Ostrowski 1998; Baring 1999, Achterberg et al. 2001; Ellison & Double 2002), and corresponds to the special case of compression ratios of \( r = 3 \) and the particular assumption of small scattering (pitch angle diffusion), specifically for incremental changes \( \theta_{\text{scatt}} \) in a particle’s momentum with angle \( \theta_{\text{scatt}} \ll 1/\Gamma_1 \). Here we explore departures from this particular case that are appropriate for burst studies.

### 2.1 Relativistic Shocks: an Array of Spectral Indices

The spectral index of the power-law distribution is a declining function of the Lorentz factor \( \Gamma_1 \) for a fixed compression ratio, a characteristic evident in Kirk & Schneider (1987a), Ballard & Heavens (1991), and Kirk et al. (2000) for the case of pitch angle scattering, and a property that extends to large angle scattering (Ellison, Jones & Reynolds 1990; Baring, 1999; Ellison...
& Double 2004). Faster shocks, if parallel, generate flatter distributions if $r$ is held constant (e.g. see the parallel shock, $\Theta_{Bn1} = 0^\circ$ case in Fig. 2), a consequence of the increased kinematic energization occurring at relativistic shocks. A tabulation of this property, namely $\sigma$ values for different $r$ in the case of pitch angle diffusion, is given in Baring (2004), and analytic approximations are derived in Keshet & Waxman (2004). Note that imposing a specific equation of state such as the Jüttner-Synge one renders $r$ a function of $\Gamma_1$ so that this monotonicity property can disappear, as evinced in Fig. 2 of Kirk et al. (2000; see also Keshet & Waxman 2004). Moreover, for significant field obliquities, the trend with shock speed is reversed, as is evident in Fig. 2.

Astrophysical models usually invoke the canonical compression ratio $r = 3$, the well-known result for a relativistic, purely hydrodynamic shock possessing an ultrarelativistic equation of state. However, in cases where the magnetic field becomes dynamically important (e.g. the termination shock for the Crab pulsar wind: Kennel & Coroniti 1984), the strong fields can weaken magnetohydrodynamic shocks considerably, just as they do in non-relativistic situations. Moreover, in ultrarelativistic shocks, where pressure anisotropy can be significant, Double et al. (2004) observed that the shock could be strengthened or weakened, depending on the nature of the pressure anisotropy, which must be a significant function of the angle, $\Theta_{Bn1}$, the upstream field makes to the shock normal. Hence, it is anticipated that $\sigma$ will be a function of $\Theta_{Bn1}$. The influence of pressure anisotropy on the shock compression will be greatest in cases where the index is low, i.e. $\sigma \lesssim 2$, so that the accelerated particles can be influential in determining the dynamics of the (non-linear) shock.

Also of interest is the fact that the slope of the nonthermal particle distribution depends on the nature of the scattering, a feature evident in the works of Ellison, Jones & Reynolds (1990), Bednarz & Ostrowski (1998) and Baring (1999). The asymptotic, ultrarelativistic index of 2.23 is realized only in the mathematical limit of pitch angle diffusion (PAD), where the particle momentum is stochastically deflected on arbitrarily small angular (and therefore temporal) scales. In practice, PAD results when the scattering angle $\theta_{\text{scatt}}$ is smaller than the Lorentz cone angle $1/\Gamma_1$ in the upstream region. In such cases, particles diffuse in the region upstream of the shock only until their angle to the shock normal exceeds around $1/\Gamma_1$. Then they are rapidly swept to the downstream side of the shock.

Particle distributions obtained from the Monte Carlo simulation of acceleration at relativistic shocks developed by Ellison, Jones & Reynolds (1990) are exhibited in Fig. 1. They demonstrated that for large angle scattering (LAS, with $\theta_{\text{scatt}} \sim \pi$) the spectrum is highly structured and much flatter than $E^{-2}$. Such a case is exhibited in the Figure. The structure is kinematic in origin, where large angle deflections lead to distribution of fractional energy gains between unity and $\Gamma_1^2$. Gains like this are kinematically analogous to the en-
Fig. 1. Particle distributions from a parallel ($\Theta_{Bn1} = 0$) relativistic shock of $r = 3$ and Lorentz factor $\Gamma_1 = 5$, obtained from a Monte Carlo simulation (Ellison, Jones & Reynolds 1990; Baring, 1999). Scattering is modeled by randomly deflecting particle momenta by an angle $\theta_{\text{scatt}}$ within a cone whose axis coincides with the momentum prior to scattering. Distributions are depicted for three cases, $\theta_{\text{scatt}} \leq 14^\circ$, corresponding to pitch angle diffusion (PAD), large angle scattering (LAS: $\theta_{\text{scatt}} \leq \pi \gg 1/\Gamma_1$), and an intermediate case (dotted histogram). The distributions are divided by the $E^{-2.23}$ ultra-relativistic power-law determined by Kirk et al. (2000).

Energization of photons by relativistic electrons in inverse Compton scattering, and are much larger on average than those realized in PAD (see Gallant & Achterberg 1999; Baring 1999). Each structured spectral segment in Fig. 1 corresponds to an increment in the number of shock crossings, successively from $1 \rightarrow 3 \rightarrow 5 \rightarrow 7$ etc., as illustrated by Baring (1999), that eventually smooth out to asymptotically approach an index of $\sigma \sim 1.5$. Clearly, such highly-structured distributions have not been inferred from radiation emission in gamma-ray bursts or any other astrophysical objects. Note that the $\Gamma_1 = 5$ results depicted here are entirely representative of ultrarelativistic shocks.
An intermediate case is also depicted in Fig. 1, with $\theta_{\text{scatt}} \sim 4/\Gamma_1$. The spectrum is smooth, like the PAD case, but the index is lower than 2.23. Magnetic turbulence could easily be sufficient to effect scatterings on the order of these angles, a contention that becomes even more salient for ultrarelativistic shocks with $\Gamma_1 \gg 10$. Clearly a range of indices can be supported when $\theta_{\text{scatt}}$ is chosen to be of the order of $1/\Gamma_1$, and the scattering corresponds to the transition between the PAD and LAS limits. Hence, it is expected that various astrophysical systems will encompass a range of scattering properties. Accordingly, the continuous and monotonically decreasing behavior of $\sigma$ with $\theta_{\text{scatt}}$, as indicated in the exposition of Ellison & Double (2004), highlights the significant range of distribution indices in relativistic shocks.

In relativistic shocks, the diversity of spectral indices is enhanced by transport properties orthogonal to the mean field direction. The diffusion of particles across mean field lines, becomes a critical element in the discussion of oblique or perpendicular shocks. In non-relativistic shocks, when the upstream angle $\Theta_{\text{Bn}1}$ of the field to the shock normal is significant, diffusion of particles in the downstream region struggle to compete with convective losses, and transport back upstream of the shock layer becomes inefficient. This leads to the quenching of injection of thermal particles of speed $v > u_1$, which fail to return to the shock after one crossing to the downstream side. Accordingly, for $\Theta_{\text{Bn}1} \approx 30^\circ$, the Fermi acceleration process ceases when transport across field lines is suppressed (Baring, Ellison & Jones 1994), and for $\Theta_{\text{Bn}1} < 30^\circ$, while power-law superthermal distributions are realized, their normalization is a strongly declining function of $\Theta_{\text{Bn}1}$.

In relativistic shocks, this phenomenon translates to a dramatic steepening of the distribution above thermal energies. When $u_1 \sim c$, an oblique shock is inherently superluminal, so that convective losses are pervasive for all particle speeds, not just slightly suprathermal ones. Such losses must diminish the nonthermal population, and since the loss rate is purely a function of particle speed $v$ (Peacock 1981; Jones & Ellison 1991), which is effectively pinned at $v \approx c$, and $u_2$, the overall effect is to increase the spectral index while retaining power-law character. Monte Carlo model indices are illustrated in Fig. 2, where the simulation output was acquired in the absence of cross field diffusion (i.e. for perpendicular spatial diffusion coefficient $\kappa_\perp = \lambda_\perp v/3 = 0$, corresponding to weak turbulence). Increasing $\Theta_{\text{Bn}1}$ results in a rapid rise in $\sigma$ corresponding to a suppression of acceleration. Essentially, for $\Theta_{\text{Bn}1} \gtrsim 25^\circ$, acceleration is virtually non-existent for $\Gamma_1 u_1/c \approx 1$. Note that $\kappa_\parallel = \lambda_\parallel v/3$ is the component of the spatial diffusion coefficient parallel to the field, so that $\kappa_\parallel/u_1$ defines the effective spatial scale of diffusion along the field lines.

If the shocked plasma is strongly turbulent, the system will be driven towards the Bohm-diffusion limit, where diffusion coefficients are similar parallel and perpendicular to the field, i.e. $\kappa_\perp \sim \kappa_\parallel$, and transport is effectively
isotropic. Efficient transport across field lines returns the particles to the shock from the downstream region, effectively circumventing convective losses, and accordingly flattening the power-law distribution. In such cases, the strength of the turbulence renders quasi-perpendicular shocks much like parallel ones, and the distinction of field obliquity becomes less meaningful. It is anticipated that transport near the Bohm limit would be essential to generate $\sigma \lesssim 3$, i.e. indices relevant for acceleration applications to burst models. This is borne out in Bednarz & Ostrowski (1998) and the recent work of Ellison & Double (2004), whose test-particle Monte Carlo simulation results of exhibited the expected monotonic decrease in $\sigma$ with an increase in $\kappa_\perp / \kappa_\parallel$. 

Fig. 2. Particle distribution indices $\sigma$, for $dn/dp \propto p^{-\sigma}$, from oblique ($\Theta_{\text{Bn}1} > 0$) relativistic shocks of $r = 3$ as a function of $\Gamma_1 \beta_1$, obtained from a Monte Carlo simulation (Ellison, Jones & Reynolds 1990; Baring 1999) in the limit of pitch angle diffusion. Results are depicted for the case of zero diffusive transport perpendicular to the mean field, i.e., $\kappa_\perp = 0$ for the component, perpendicular to $\mathbf{B}$, of the spatial diffusion coefficient $\kappa = \lambda v / 3$, where $\lambda$ is a particle’s diffusive mean free path. The index is insensitive to $\Theta_{\text{Bn}1}$ for non-relativistic shocks, but rapidly increases with obliquity for relativistic ones, underlining their inherent inefficiency.
It must be remarked that the transport of particles in the shock environment possesses a complex dependence on the nature of the dynamic fields. Niemiec & Ostrowski (2004) very recently explored the acceleration process at relativistic shocks by computing particle trajectories near a shock in the presence of injected, strong field turbulence. They found that (i) the spectral index was dependent on the strength of the turbulence, and more interestingly, (ii) that large perturbation amplitudes $\delta B/B \gtrsim 1$ could actually render a steepening of the distribution of accelerated particles for oblique, subluminal shocks. Niemiec & Ostrowski (2004) contended that this characteristic was largely a consequence of reduced reflection in the shock layer, and observed that the effect was generally reversed in oblique, superluminal shocks, where increasing $\delta B/B$ flattened the distribution somewhat. Their investigations, and the Monte Carlo technique, of course do not explore quasi-coherent electrodynamic acceleration that results from charge separation potentials and currents in the shock layer; such plasma physics properties are best probed using particle-in-cell (PIC) simulations, which have been recently exploited by Silva et al. (2003) and Nishikawa et al. (2003) to study the development of the Wiebel instability and associated acceleration in relativistic plasma shocks. These injected turbulence and PIC simulations add to the evidence that the spectrum of particles accelerated at relativistic shocks is not universal.

### 2.2 Modeling Observed GRB Prompt Emission

The sensitivity of the power-law index to shock obliquity and the nature of turbulent transport immediately indicate that GRB spectra should possess a diversity of indices, if a shock acceleration model is applicable to the burst paradigm. This is in fact manifested in the energy range well above the $\sim 1$ MeV peak of emission in data taken from the EGRET experiment on the Compton Gamma-Ray Observatory (CGRO), where the half dozen or so bursts seen at high energies have a broad range of spectral indices (Dingus 1995), namely $\alpha \sim 2 - 3.7$ for $dn/d\gamma \propto \gamma^{-\alpha}$. This result suffers from limited statistics due to (i) the nature of bursts, and (ii) to EGRET's field of view being more constrained than that for BATSE, the principal GRB experiment on CGRO. The GLAST mission will provide a more refined determination of the distribution of burst indices above 30 MeV after its launch in 2007.

The EGRET data suggest that relatively flat indices are more common, though there is an obvious observational bias against distinguishing $\alpha \gtrsim 6$ cases, since poor statistics at the uppermost energies will degrade index determination in such cases. If particle acceleration in bursts is indeed this efficient, then highly oblique shocks cannot be present, unless the turbulence is extremely strong; the results of Niemiec & Ostrowski (2004) support this contention. For prompt EGRET emission, the prevailing scenario is that shocks
internal to the GRB flow/blast wave are responsible for the dissipative conversion of bulk kinetic energy to observable radiation (e.g. see Piran 1999; Meszaros 2002). These shocks are necessarily mildly-relativistic, so $\sigma \sim 3 - 4$ values are reasonable for near the Bohm diffusion, even if the shocks are highly oblique. In contrast, optical afterglow models invoke the outer blast wave shock as the site for their energization, and in all probability, this ultrarelativistic shock is quasi-perpendicular. In such a shock environment, it is difficult to generate indices $\sigma \sim 3$ even near the Bohm limit, so it is unclear how well $\Gamma_1 \gg 1$ shocks will be able to model burst afterglow spectra.

The power-law index is not the only acceleration characteristic germane to the GRB problem: the shapes of the particle distributions at thermal and slightly suprathermal energies are also pertinent. This energy domain samples particle injection or dissipational heating in the shock layer, and is readily probed for electrons by the spectrum of prompt GRB emission in the BATSE band. Tavani (1996) obtained impressive spectral fits to several bright BATSE bursts using a phenomenological electron distribution and the synchrotron emission mechanism. This has been a driver for the interpretation of burst spectra. There are issues with fitting low energy (i.e. $\lesssim 100$ keV) spectra in about 1/3 of bursts (e.g. Preece et al. 1998) in the synchrotron model, yet this emission mechanism still remains the most popular candidate today. Tavani's work did not directly address theoretical characteristics of distributions of accelerated particles at slightly suprathermal energies.

Perspectives based on acceleration theory underpinned the recent analysis of Baring & Braby (2004), who pursued a program of spectral fitting of GRB emission using a linear combination of thermal and non-thermal electron populations. These fits demanded that the preponderance of electrons that are responsible for the prompt emission reside in an intrinsically non-thermal population. This requirement strongly contrasts particle distributions obtained from acceleration simulations, exemplified by those depicted in Fig. 1. The consequence is obviously a potential conflict for acceleration scenarios where the non-thermal electrons are drawn directly from a thermal gas (the virtually ubiquitous case), unless radiative efficiencies only become significant at highly superthermal energies. This does not necessarily mean that acceleration at relativistic shocks is not operating in bursts. It is possible that somehow, relativistic shocks can suppress thermalization of electrons, though such a conjecture has no definitive simulational evidence to support it at present. A potential resolution to this dilemma is that strong radiative self-absorption could be acting, in which case the BATSE spectral probe is not actually sampling the thermal electrons. It is also possible that other radiation mechanisms such as pitch-angle synchrotron, or jitter radiation may prove more desirable. A goal of future work will be to ascertain whether a shock acceleration paradigm can be truly consistent with the GRB emission that is observed.
3 Conclusions

This paper has discussed two key acceleration issues for models of gamma-ray burst sources, namely expectations for the power-law index $\sigma$ of the non-thermal population, and the efficiency for which these particles are injected into the acceleration process. The recent analysis of Kirk et al. (2000), applicable for the specific case of pitch angle diffusion at plane parallel shocks, has demonstrated that the index of this power-law asymptotically approaches $\sigma = 2.23$ as the Lorentz factor $\Gamma_1$ of the upstream flow in the shock rest frame tends to infinity. Here it is illustrated how this widely-quoted result is not universal, and that an array of indices are possible in general. Results from a kinetic Monte Carlo simulation of diffusive shock acceleration are presented. These indicate that the value of $\sigma$ is sensitive to the nature of the scattering, becoming much smaller than 2.23 when the particle transport experiences angular deflections larger than around $1/\Gamma_1$. The simulated distributions in $\Gamma_1 \gg 1$ cases exhibit a rapid steepening (i.e., higher $\sigma$) as the magnetic field obliquity $\Theta_{Bn1}$ of the shock rises above zero, in the particular case where diffusion perpendicular to the mean field is absent: efficient acceleration is effectively quenched in moderately oblique and quasi-perpendicular truly relativistic shocks unless there is strong cross field diffusion. The array of possible values of $\sigma$ is commensurate with EGRET data on a handful of bursts. This characteristic favors an internal shock model for the prompt emission, where the shocks are only mildly-relativistic in the comoving expansion frame, and the spread of $\sigma$ values is narrower. It is also noted that the acceleration simulations only inject a minority of thermal particles into the diffusive acceleration process, contrasting electron distributions inferred in spectral fits for bright CGRO bursts. This poses a potential conflict for acceleration models that motivates further exploration of the energization of electrons via detailed hydrogenic and pair plasma simulations of shock acceleration.

4 References

Achterberg, A., Gallant, Y. A.; Kirk, J. G., Guthmann, A. W. Particle acceleration by ultrarelativistic shocks: theory and simulations. M.N.R.A.S. 328, 393–408, 2001.
Ballard, K. R., Heavens, A. F. First-order Fermi acceleration at oblique relativistic magnetohydrodynamic shocks. M.N.R.A.S. 251, 438–448, 1991.
Ballard, K. R., Heavens, A. F. Shock acceleration and steep-spectrum synchrotron sources. M.N.R.A.S. 259, 89–94, 1992.
Baring, M. G. Acceleration at Relativistic Shocks in Gamma-Ray Bursts. in Proc. of the 26th ICRC, Vol. IV, p. 5–8, [astro-ph/9910128], 1999.
Baring, M. G. Nucl. Phys. B Proc. Supp. 136, 198–207, Diffusive Shock Ac-
acceleration of High Energy Cosmic Rays. [astro-ph/0409303], 2004.
Baring, M. G., Braby, M. L. A Study of Prompt Emission Mechanisms in Gamma-Ray Bursts. ApJ 613, 460–476, 2004.
Baring, M. G., Ellison, D. C., Jones, F. C. Monte Carlo Simulations of Particle Acceleration at Oblique Shocks. ApJ Supp. 90, 547–552, 1994.
Baring, M. G., Harding, A. K. The Escape of High-Energy Photons from Gamma-Ray Bursts. ApJ 491, 663–680, 1997.
Baring, M. G., Kirk, J. G. The modification of relativistic shock fronts by accelerated particles. Astron. Astrophys. 241, 329–342, 1991.
Bednarz, J., Ostrowski, M. Energy Spectra of Cosmic Rays Accelerated at Ultrarelativistic Shock Waves. Phys. Rev. Lett. 80, 3911–3914, 1998.
Blandford, R. D., Ostriker, J. P. Particle acceleration by astrophysical shocks. ApJ 221, L29–L32, 1978.
Dingus, B. L. EGRET Observations of > 30 MeV Emission from the Brightest Bursts Detected by BATSE. Astr. Space Sci. 231, 187–190, 1995.
Double, G. P., Baring, M. G., Jones, F. C., Ellison, D. C. Magnetohydrodynamic Jump Conditions for Oblique Relativistic Shocks with Gyrotropic Pressure. ApJ 600, 485–500, 2004.
Ellison, D. C., Double, G. P. Nonlinear particle acceleration in relativistic shocks. Astroparticle Phys. 18, 213–228, 2002.
Ellison, D. C., Double, G. P. Diffusive shock acceleration in unmodified relativistic, oblique shocks. Astroparticle Phys. 22, 323–338, 2004.
Ellison, D. C., Jones, F. C., Reynolds, S. P. First-order Fermi particle acceleration by relativistic shocks. ApJ 360, 702–714, 1990.
Gallant, Y. A., Achterberg, A. Ultra-high-energy cosmic ray acceleration by relativistic blast waves. M.N.R.A.S. 305, L6–L10, 1999.
Heavens, A. F., Drury, L. O’C. Relativistic shocks and particle acceleration. M.N.R.A.S. 235, 997–1009, 1988.
Jones, F. C., Ellison, D. C. The plasma physics of shock acceleration. Space Sci. Rev. 58, 259–346, 1991.
Kennel, C. F., Coroniti, F. V. Confinement of the Crab pulsar’s wind by its supernova remnant. ApJ 283, 694–709, 1984.
Keshet, U., Waxman, E. The spectrum of particles accelerated in relativistic, collisionless shocks. preprint, [astro-ph/0408489], 2004.
Kirk, J. G., Guthmann, A. W., Gallant, Y. A., Achterberg, A. Particle Acceleration at Ultrarelativistic Shocks: An Eigenfunction Method. ApJ 542, 235–242, 2000.
Kirk, J. G., Schneider, P. On the acceleration of charged particles at relativistic shock fronts. ApJ 315, 425–433, 1987a.
Kirk, J. G., Schneider, P. Particle acceleration at shocks - A Monte Carlo method. ApJ 322, 256–265, 1987b.
Kirk, J. G., Webb, G. M. Cosmic-ray hydrodynamics at relativistic shocks. ApJ 331, 336–342, 1988.
Mészáros, P. Ann. Rev. Astron. Astr. Theories of Gamma-Ray Bursts. 40, 137–169, 2002.
Niemiec, J., Ostrowski, M. Cosmic-Ray Acceleration at Relativistic Shock Waves with a “Realistic” Magnetic Field Structure. ApJ 610, 851–867, 2004.

Nishikawa, K.-I., Hardee, P., Richardson, G., et al. Particle Acceleration in Relativistic Jets Due to Weibel Instability. ApJ 595, 555–563, 2003.

Ostrowski, M. Monte Carlo simulations of energetic particle transport in weakly inhomogeneous magnetic fields. I - Particle acceleration in relativistic shock waves with oblique magnetic fields. M.N.R.A.S. 249, 551–559, 1991.

Paczyński, B. Gamma-ray bursters at cosmological distances. ApJ 308, L43–L46, 1986.

Peacock, J. A. Fermi acceleration by relativistic shock waves. M.N.R.A.S. 196, 135–152, 1981.

Piran, T. Phys. Rep. Gamma-ray bursters and the fireball model. 314, 575–667, 1999.

Preece, R. D., Briggs, M. S., Mallozzi, R. S., et al. The Synchrotron Shock Model Confronts a “Line of Death” in the BATSE Gamma-Ray Burst Data. ApJ 506, L23–L26, 1998.

Rees, M. J., Mészáros, P. Relativistic fireballs – Energy conversion and time-scales. M.N.R.A.S. 258, 41–43, 1992.

Schneider, P., Kirk, J. G. Fermi acceleration at shocks with arbitrary velocity profiles. ApJ 323, L87–L90, 1987.

Silva, L. O., Fonseca, R. A., Tonge, J. W., et al. Interpenetrating Plasma Shells: Near-equipartition Magnetic Field Generation and Nonthermal Particle Acceleration. ApJ 596, L121–L124, 2003.

Tavani, M. Shock Emission Model for Gamma-Ray Bursts. Phys. Rev. Lett. 76, 3478–3481, 1996.