Using Gamma-Ray Burst Prompt Emission to Probe Relativistic Shock Acceleration

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**Abstract**

It is widely accepted that the prompt transient signal in the 10 keV – 10 GeV band from gamma-ray bursts (GRBs) arises from multiple shocks internal to the ultra-relativistic expansion. The detailed understanding of the dissipation and accompanying acceleration at these shocks is a currently topical subject. This paper explores the relationship between GRB prompt emission spectra and the electron (or ion) acceleration properties at the relativistic shocks that pertain to GRB models. The focus is on the array of possible high-energy power-law indices in accelerated populations, highlighting how spectra above 1 MeV can probe the field obliquity in GRB internal shocks, and the character of hydromagnetic turbulence in their environs. It is emphasized that diffusive shock acceleration theory generates no canonical spectrum at relativistic MHD discontinuities. This diversity is commensurate with the significant range of spectral indices discerned in prompt burst emission. Such system diagnostics are now being enhanced by the broadband spectral coverage of bursts by the *Fermi* Gamma-Ray Space Telescope; while the Gamma-Ray Burst Monitor (GBM) provides key diagnostics on the lower energy portions of the particle population, the focus here is on constraints in the non-thermal, power-law regime of the particle distribution that are provided by the Large Area Telescope (LAT).

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1 Introduction

Despite rapid evolution of the understanding of gamma-ray bursts over the last decade since the first redshift determinations established a cosmological distance scale, there is still much to be learned about associations, progenitors, and the radiation processes active in both the prompt and afterglow emission regions. The most popular burst paradigm for the genesis of the prompt burst emission is of radiative dissipation at internal shocks that accelerate particles (Rees & Meszaros 1992; Piran 1999; Meszaros 2002). Within this scenario, it is of great interest to understand what physical conditions in the shocked environs can elicit the observed high energy indices and the spectral structure around the MeV-band peak. It is clear that the measurement of the high energy spectral index provides a key constraint on the interpretation of the electron acceleration process. To provide insights into these conditions, one turns to models of diffusive shock acceleration in relativistic systems.

A core property of acceleration at the relativistic shocks that are presumed to seed prompt GRB radiation is that the distribution functions \( f(p) \) are inherently anisotropic. This renders the power-law indices and other distribution characteristics sensitive to directional influences such as the magnetic field orientation, and the nature of MHD turbulence that often propagates along the field lines. Consequently, familiar results from relativistic shock acceleration theory such as the so-called canonical \( \sigma = 2.23 \) power-law index (e.g. Kirk et al. 2000) are of fairly limited applicability, though they do provide useful insights. This diversity is fortunate since the GRB database so far has exhibited a substantial range of spectral indices, so any universal signature in the acceleration predictions would be unnecessarily limiting.

This paper explores some of the features of diffusive shock acceleration using results from a test particle Monte Carlo simulation, and addresses probes of the theoretical parameter space imposed by extant GRB observations above the MeV spectral break. The Monte Carlo approach (Ellison, Jones & Reynolds 1990; Ellison & Double 2004; Niemiec & Ostrowski 2004; Stecker, et al. 2007) is one of several major techniques devised to model particle acceleration at shocks; others include semi-analytic solutions of the diffusion-convection equation (Kirk & Heavens 1989; Kirk et al. 2000), and particle-in-cell (PIC) full plasma simulations (Hoshino, et al. 1992; Nishikawa, et al. 2005; Medvedev, et al. 2005; Spitkovsky 2008). Each has its merits and limitations. Tractability of the analytic approaches generally restricts solution to power-law regimes for the \( f(p) \) distributions. PIC codes are rich in their information on shock-layer electrodynamics and turbulence. To interface with GRB data, a broad dynamic range in momenta is desirable, and this is the natural niche of Monte Carlo simulation techniques, the focus of this paper.
Useful diagnostics (Baring & Braby 2004; Baring 2009) on $f(p)$ have already been enabled by data from the BATSE and EGRET instruments on the Compton Gamma-Ray Observatory (CGRO) for a few bright bursts. Significant advances are anticipated in the understanding of such constraints in the next few years, afforded by the broad spectral coverage and sensitivity of the GBM and LAT experiments on NASA’s Fermi Gamma-Ray Space Telescope; this is already being realized.

2 Diffusive Acceleration at Relativistic Shocks

The simulation used here to model diffusive acceleration in relativistic planar shocks is a kinematic Monte Carlo technique that has been employed extensively in supernova remnant and heliospheric contexts, and is described in detail in numerous papers (Ellison, Jones & Reynolds 1990, hereafter EJR90; Jones & Ellison 1991; Ellison, et al. 1995; Ellison & Double 2004; Summerlin & Baring 2006; Baring 2009). It is conceptually similar to Bell’s (1978) test particle approach to diffusive shock acceleration. Test particles that are injected upstream gyrate in laminar electromagnetic fields, their trajectories being governed by a relativistic Lorentz force equation in the frame of the shock. In general, the fluid frame magnetic field is inclined at an angle $\Theta_{\text{Bf1}}$ to the shock normal. Because the shock is moving with a velocity $u(x)$ relative to the plasma rest frame, there is, in general, a $u \times B$ electric field in addition to the bulk magnetic field. Particle interactions with Alfvén wave and other hydromagnetic turbulence are modeled by using a phenomenological scattering of the charges in the rest frame of the plasma. The scattering precipitates spatial diffusion of particles along magnetic field lines, and to a varying extent, across them as well. The scatterings are also assumed to be quasi-elastic, an idealization that is usually valid because in most astrophysical systems the flow speed far exceeds the Alfvén speed, and contributions from stochastic second-order Fermi acceleration are small. The diffusion permits a minority of particles to transit the shock plane numerous times, gaining energy with each crossing via the shock drift and first-order Fermi processes.

A continuum of scattering angles, between large-angle or small-angle cases, can be modeled by the simulation. In the local fluid frame, the time, $\delta t_f$, between scatterings is coupled (EJR90) to the mean free path, $\lambda$, and the maximum scattering (i.e. momentum deflection) angle, $\theta_{\text{scatt}}$, via $\delta t_f \approx \lambda \theta_{\text{scatt}}^2/(6v)$ for particles of speed $v \approx c$. Usually $\lambda$ is assumed to be proportional to a power of the particle momentum $p$ (see EJR90 and Giacalone, et al. 1992) for microphysical justifications for this choice), and for simplicity it is presumed to scale as the particle gyroradius, $r_g$, i.e. $\lambda = \eta r_g \propto p$. The parameter $\eta$ in the model is a measure of the level of turbulence present in the system, coupling directly to the amount of cross-field diffusion, such that $\eta = 1$ corresponds to the
isotropic Bohm diffusion limit, where the field fluctuations satisfy \( \delta B / B \sim 1 \).

In kinetic theory, \( \eta \) couples the parallel \( (\kappa_{\parallel} = \lambda v / 3) \) and perpendicular \( (\kappa_{\perp}) \) spatial diffusion coefficients via the relation \( \kappa_{\perp} / \kappa_{\parallel} = 1 / (1 + \eta^2) \) (Forman, et al. 1974; Ellison, et al. 1995). In parallel shocks, where the \( B \) field is directed along the shock normal \( (\Theta_{Bf1} = 0) \), \( \eta \) has only limited impact on the resulting energy spectrum, principally determining the diffusive spatial scale normal to the shock. However, in oblique relativistic shocks where \( \Theta_{Bf1} > 0 \), the diffusive transport of particles across the field (and hence across the shock) becomes critical to retention of them in the acceleration process. Accordingly, for such systems, the interplay between the field angle and the value of \( \eta \) controls the spectral index of the particle distribution (Ellison & Double 2004; Baring 2004), a feature that is central to the interpretation of GRB spectra below.

The test particle assumption adopted in this paper is appropriate as long as the energy density \( U_{cr} \) of accelerated particles is much less than that of the thermal gas \( U_g \). This is generally the case for the simulation results presented here. For the most energetic particles to establish \( U_{cr} \gtrsim U_g \) demands very flat distributions, namely \( \sigma < 2 \) if \( dN/dp = 4\pi p^2 f(p) \propto p^{-\sigma} \). It can be inferred from the distributions in Fig. 1 that those cases that satisfy this condition are inefficient at injecting from thermal energies, so that they generate \( U_g / U_{cr} \ll 1 \). These contrast non-linear acceleration scenarios where the non-thermal population modifies the Rankine-Hugoniot MHD structure of the shock because \( U_{cr} \gtrsim U_g \), thereby inducing spectral concavity in the energetic tail. Such non-linear cases have been explored extensively for the contexts of galactic cosmic rays produced in supernova remnant shells (e.g. Ellison, et al. 2000) and the Earth’s bow shock (Ellison, Möbius & Paschmann 1990, hereafter EMP90) Generally, as is apparent in Fig. 2 below, GRB spectra are too steep to sample the non-linear acceleration regime. Moreover, in the case of GRB 080916c, the power-law character above 1 MeV is well established (Abdo, et al. 2009a): no evidence of any spectral concavity can be discerned. While some models of GRB dissipation in the literature assume that large fractions (i.e. \( \gtrsim 30\% \)) of the total lepton energy density reside in the accelerated electron population (perhaps adopting truncated power-laws), there is no theoretical mandate for such from the perspective of diffusive shock acceleration theory. This assertion applies not only to results from Monte Carlo codes such as are presented here, but also to distributions generated in PIC simulations (e.g. Spitkovsky 2008).

The mildly-relativistic shock regime \( u \lesssim c \) forms the focus of this exposition, since this is germane to internal GRB shock models that invoke shock formation via the collision of two ultra-relativistic shells. The discussion will first outline the core characteristics of the diffusive acceleration process, before moving onto constraints on theoretical parameters imposed by the observed spectral indices of prompt emission in bright gamma-ray bursts.
2.1 Acceleration Characteristics for Relativistic Shocks

As mentioned above, the key property of diffusive acceleration at relativistic shocks that distinguishes them from their non-relativistic counterparts is their intrinsic anisotropy. This is driven by the powerful convective influence that enables efficient loss of particles away from and downstream of the shock. The result of this loss is a general difficulty in generating flat distributions of shock-accelerated particles, particularly for so-called superluminal (oblique) relativistic discontinuities. Here, the array of possible distribution indices $\sigma$ is highlighted, spawned by the sensitivity of both the energization in, and escape from, the shock layer, to (i) the size of the momentum deflection angle $\theta_{\text{scatt}}$, (ii) the frequency or relative mean free path $\lambda/r_g$ of scatterings, and (iii) the upstream field obliquity $\Theta_B$, a quantity derived from the global MHD structure of the shock. In this paper, the focus will be on the latter two influences.

Before investigating them, it is appropriate to mention the first effect, which was originally identified for relativistic shocks in EJR90. When the diffusion in the shock layer samples large field fluctuations $\delta B/B \sim 1$, it corresponds to large momentum deflections, delineating the regime of large angle scattering (LAS) with $4/\Gamma_1 \lesssim \theta_{\text{scatt}} \lesssim \pi$, where $\Gamma_1$ is the upstream flow’s incoming Lorentz factor. Such large deflections produce huge gains in particle energy, of the order of $\Gamma_1^2$ in a single scattering and therefore also in successive shock crossings. These gains are kinematic in origin, and are akin to those in inverse Compton scattering. The result is an acceleration distribution $dN/dp$ that is highly structured and much flatter on average than $p^{-2}$, first noted by EJR90. The bumpy structure is kinematic in origin and becomes more pronounced for large $\Gamma_1$ (Baring 2004; Ellison & Double 2004; Stecker, et al. 2007, hereafter SBS07; Baring 2009). For ultra-relativistic shocks, when $p \gg mc$, the bumps asymptotically relax to form a power-law distribution $dN/dp \propto p^{-\sigma}$, as is mandated by the concomitant lack of a momentum scale, with an index in the range of $\sigma \sim 1.6$ (SBS07). From the plasma physics perspective, magnetic turbulence in relativistic shocks could easily be sufficient to effect scatterings on intermediate to large angular scales $\theta_{\text{scatt}} \gtrsim 1/\Gamma_1$, a proposition that becomes more enticing for ultrarelativistic shocks.

Particle distributions for $\theta_{\text{scatt}} \lesssim 1/\Gamma_1$ are much smoother in appearance, and often necessarily steeper, at least for superluminal regimes. Intermediate scattering angles $\theta_{\text{scatt}} \sim 1/\Gamma_1$ generate smooth distributions (SBS07, Baring 2009), much like those for (but flatter than) the more familiar small angle scattering (SAS, often called pitch angle diffusion, PAD) which will constitute the regime of focus hereafter. This regime has spawned the often cited asymptotic, ultrarelativistic index of $\sigma = 2.23$ for $dN/dp \propto p^{-\sigma}$ (Kirk et al. 2000; see also Bednarz & Ostrowski 1998; Baring 1999). This special result is
realized only for parallel shocks with $\Theta_{Bf1} = 0^\circ$ in the mathematical limit of small angle scattering $\theta_{\text{scatt}} \ll 1/\Gamma_1$, where the particle momentum is stochastically deflected on arbitrarily small angular (and therefore temporal) scales. In such cases, particles diffuse in the region upstream of the shock only until their velocity’s angle to the shock normal exceeds around $1/\Gamma_1$, after which they are rapidly swept downstream of the shock. The lower kinematic energy gains in shock transits more than compensate for the accompanying slightly higher shock-layer retention rates, producing a steeper distribution under SAS conditions.

Representative particle differential distributions $dN/dp$ that result from the simulation of diffusive acceleration at mildly-relativistic (internal GRB) shocks of speed $\beta_{1x} = 0.5$ are depicted in Figure 1 (see Ellison & Double 2004, and SBS07) for $\Gamma_1 \gg 1$ simulation results). Here, the subscript $x$ denotes components along the shock normal. These distributions are equally applicable to electrons or ions, and were generated for $\theta_{\text{scatt}} \lesssim 10^\circ$, i.e. in the SAS regime. Results are displayed for two different upstream fluid frame field obliquities, namely $\Theta_{Bf1} = 48.2^\circ$ and $\Theta_{Bf1} = 59.1^\circ$. These define shocks with two distinct de Hoffman-Teller (1950; HT) frame dimensionless speeds $\beta_{1\text{HT}} = \beta_{1x}/\cos \Theta_{Bf1}$. The HT frame is the shock rest frame where the flow is everywhere parallel to the local magnetic field. Note that the distributions in the Figure were measured in the normal incidence frame (NIF), the shock rest frame in which the upstream fluid flows in along the shock normal; in this frame, the magnetic field vectors are generally not parallel to those in the fluid or HT frames. The HT flow speed $\beta_{1\text{HT}}$ corresponds to a physical speed when it is less than unity, i.e. the upstream field obliquity satisfies $\cos \Theta_{Bf1} > \beta_{1x}$; the shock is then called subluminal. When mathematically $\beta_{1\text{HT}} > 1$, no Lorentz boost from the local fluid frame can render the flow parallel to $B$ and de Hoffman-Teller frame does not exist: the shock is said to be superluminal.

The distributions clearly exhibit an array of indices $\sigma$, including very flat power-laws, that are not monotonic functions of either the field obliquity $\Theta_{Bf1}$ nor the key diffusion parameter $\eta = \lambda/r_g$. However, it is striking that the normalization of the power-laws relative to the low momentum thermal populations is a strongly-declining function of $\lambda/r_g$. This is a consequence of a more prolific convection downstream away from the shock that suppresses diffusive injection from thermal energies into the acceleration process. Simulation runs for $\lambda/r_g \geq 10^3$ inhibit such injection by several to many orders of magnitude, and so were not displayed in the plot. Note also that the choice of the compression ratio $r = 4$ is somewhat larger than the Rankine-Hugoniot MHD value for $\beta_{1x} = 0.5$, $M_s = 4.04$ conditions, and was adopted to afford a direct comparison with the semi-analytic convection-diffusion equation results of Kirk & Heavens (1989). Details of this comparison are discussed briefly in Baring (2009).
Fig. 1. Particle distribution functions $dN/dp$ from mildly-relativistic sub-luminal shocks ($\Gamma_{1x}\beta_{1x} = 0.577$, i.e. $\beta_{1x} = u_{1x}/c = 0.5$) of upstream-to-downstream velocity compression ratio $r = u_{1x}/u_{2x} \approx 4$. Simulation results are depicted for two upstream fluid frame magnetic field obliquities, labelled by their corresponding de Hoffman-Teller frame upstream flow speeds $\beta_{1HT} = \beta_{1x}/\cos \Theta_{Bf1}$. These are in distinct groups of three: $\Theta_{Bf1} = 48.2^\circ$ ($\beta_{1HT} = 0.75$, multiplied by 100) for the upper three histograms, and $\Theta_{Bf1} = 59.1^\circ$ ($\beta_{1HT} = 0.975$) for the lower three histograms. Scattering off hydromagnetic turbulence was modeled by randomly deflecting particle momenta by an angle within a cone, of half-angle $\theta_{scatt}$, whose axis coincides with the particle momentum prior to scattering; three different ratios of the diffusive mean free path $\lambda$ to the gyroradius $r_g$ were adopted for each $\Theta_{Bf1}$. All results were for small angle scattering (SAS), when $\theta_{scatt} \lesssim 1/\Gamma_1$ and the distributions become independent of the choice of $\theta_{scatt}$. A low sonic Mach number $M_s$ was chosen so as to maximize the efficiency of injection from thermal energies.

To summarize the influence of the two key parameters that dictate the range of possible spectral indices $\sigma$, namely the field obliquity $\Theta_{Bf1}$, and the ratio $\eta = \lambda/r_g$, a parameter survey for diffusive acceleration at $\beta_{1x}$ shocks (typical of mildly-relativistic systems) is exhibited in Figure 2. Again, the small angle scattering limit was employed. To interface more directly with GRB observations, it is convenient to represent the particle power-law indices via their radiative emission equivalent, namely the high energy spectral index $\alpha_h$ (or the Band model index $\beta = -\alpha_h$ of common usage: see Band et al. 1993), for which the observed differential photon spectrum is $dn/d\varepsilon_\gamma \propto \varepsilon_\gamma^{-\alpha_h}$ above the MeV-band $\nu$-$F_\nu$ peak. The correspondence between $\sigma$ and $\alpha_h$ depends
on the emission mechanism and the model assumptions. Here, the popular quasi-isotropic synchrotron mechanism (Rees & Mészáros 1992; Tavani 1996; Piran 1999; Mészáros 2002) in bursts is adopted for this purpose. Moreover, for this illustrative agenda, it is presumed that the emission is in the strongly-cooling domain, for which an accelerated electron/pair distribution with index $\sigma$ steepens under synchrotron cooling to a power-law of index of $\sigma + 1$. With these specifications, one simply has the relation $\alpha_h = (\sigma + 2)/2$, so that $p^{-2}$ shock acceleration power-laws map over to $\varepsilon^{-2}$ photon spectra. Accordingly, the photon power-law index $\alpha_h$ is plotted as a function of $\Theta_{\text{BH}}$, with subluminal shocks constituting those with obliquities $\Theta_{\text{BH}} < 60^\circ$. There is clearly a considerable range of possible photon indices spawned by non-thermal particles accelerated in mildly relativistic shocks — the same is true for hadronic emission components, where, quite often $\alpha_h \approx \sigma$). This is a non-universality that can attractively mesh with GRB observations. Note also that the distributions in Fig. 1 correspond to indices at the obliquities marked in Fig. 2 at the top by the labels $\beta_{\text{HT}} = 0.75$ and $\beta_{\text{HT}} = 0.975$.

An obvious feature of this plot is that the dependence of $\alpha_h$ on field obliquity is non-monotonic. When $\lambda/r_g \gg 1$, the value of $\alpha_h$ at first declines as $\Theta_{\text{BH}}$ increases above zero. This leads to very flat spectra. As $\beta_{\text{HT}}$ approaches and eventually exceeds unity, this trend reverses, and $\alpha_h$ then rapidly increases with increasing shock obliquity. This dramatic steepening of the distribution in near-luminal and superluminal shocks is precipitated by inexorable convection of particles away downstream of the shock, character that is evinced in Fig. 1. Any amelioration of this rapid decline in the acceleration efficiency requires the reduction of $\lambda/r_g$ to values below around 10. Physically, this condition is tantamount to increasing the hydromagnetic turbulence to high levels that force the particle diffusion to approach isotropy, i.e. encroaching upon the Bohm diffusion limit of $\lambda/r_g \sim 1$. Then, transport of charges across the mean field becomes significant on gyration timescales, and they can be retained near the shock for sufficient times to accelerate and generate suitably flat distribution functions. Such low values of $\lambda/r_g$ render the field direction immaterial, and the shock behaves much like a parallel, subluminal shock in terms of its diffusive character. Then, $\alpha_h$ is only weakly dependent on $\Theta_{\text{BH}}$, another important property illustrated in Fig. 2.

The third key characteristic is the very flat spectra with $\alpha_h \sim 1.5$ that form from extremely flat electron distributions with $\sigma \sim 1$. The origin of these (Baring 2009) is in the coherent effect of shock drift acceleration at the shock discontinuity. This phenomenon is due to the energy gain of charges when they repeatedly encounter $u \times B$ drift electric fields (in frames other than the HT frame) in gyrations straddling the shock discontinuity; it has been widely discussed in the context of non-relativistic astrophysical and heliospheric shocks. When $\lambda/r_g \gg 1$, the charge trajectories maintain helical coherence so that for select gyrophases they can be trapped in the shock layer,
Fig. 2. Photon power-law indices $\alpha_h$ (for $dn/d\varepsilon_\gamma \propto \varepsilon_\gamma^{-\alpha_h}$) corresponding to shock acceleration simulation runs in the limit of small angle scattering, again for an upstream flow speed $\beta_{1x} \equiv u_{1x}/c = 0.5$, and a compression ratio $r = 4$. The indices are displayed as functions of the fluid frame field obliquity $\Theta_{B\parallel}$, with obliquities $\Theta_{B\parallel} > 60^\circ$ constituting superluminal shocks. The displayed simulation index results were obtained for different diffusive mean free paths $\lambda$ parallel to the mean field direction, namely $\lambda/r_g = 1$ (squares), $\lambda/r_g = 10$ (triangles), $\lambda/r_g = 10^2$ (pentagons), and $\lambda/r_g = 10^3$ (triangles), as labelled. The heavyweight horizontal line labelled GRB 080916c indicates the approximate spectral index $\alpha_h$ that is appropriate for this Fermi burst in the selected time intervals $c$ and $e$ listed in Abdo et al. (2009a). All photon indices apply to a cooled synchrotron emission scenario: see the text for a discussion.

gain energy and be reflected upstream to subsequently participate in repeated shock encounters. Particles can then efficiently gain energy by the shock drift process before they are eventually lost downstream, and the result is a distribution function approaching $dN/dp \propto p^{-1}$. Reducing $\lambda/r_g$ and thereby introducing extremely modest amounts of turbulence and associated cross-field diffusion disrupts this coherence, removes particles from the shock layer, and accordingly steepens the spectrum.
3 GRB Observations as Probes of Shock Acceleration

The shock acceleration theory results presented in Figs. 1 and 2 can now be interpreted in the light of prompt GRB observations. The focus here is on the high energy spectral index $\alpha_h$ of the power-law above the $\nu - F_\nu$ peak. This makes direct connection to data from CGRO's EGRET telescope, and now to the growing database of Fermi-LAT burst detections. To complement these probes of diffusive shock acceleration modeling of gamma-ray bursts, it must be noted that considerable insights can also be gleaned from consideration of the burst spectral shape at and below the $\nu - F_\nu$ peak. This was the principal focus of the investigation by Baring & Braby (2004), that built upon the early work on broad-band spectral fitting of bursts was provided by Tavani (1996). The constraints on particle distributions, shock acceleration interpretations and viable radiation mechanisms in bright CGRO bursts that were derived in Baring & Braby (2004) are reviewed in Baring (2009).

It should be noted that forging a direct connection between the observed $\alpha_h$ and the underlying non-thermal particle distribution index $\sigma$ is possible when the Thomson optical depth $\tau_T$ is small, and is straightforward for most bursts with good spectroscopy and well-established power-laws above 1 MeV. The Fermi-LAT bursts GRB 080916c (Abdo, et al. 2009a) and GRB 090510 (Abdo et al. 2009b) are suitable examples. Occasionally, the situation may be more complicated. For example, some models adopt high $\tau_T$ (e.g. Mészáros & Rees 2000; Pe’er & Waxman 2004; Ryde 2005) that lead to strong Comptonization/thermalization and high compactnesses that spawn rampant pair creation. These can prove viable for isolated instances when the observed spectrum is quasi-thermal (e.g. Ryde 2005), and a jet photosphere is invoked. A case in point is time interval $b$ in the Fermi-LAT burst GRB 090902b (Abdo et al. 2009c), which offers a highly-peaked and narrow spectral component that may (or may not) preclude a shock acceleration interpretation. Yet, this is an exceptional selection, and most GRB observations offer fairly clean $\alpha_h < 3.5$ determinations that permit inferences of an underlying electron or proton non-thermal distribution index $\sigma$. In the majority of extant burst detections, the non-thermal spectroscopic interpretation still remains a simpler explanation than does the non-isothermal convolution of spectra close to the ideal Planck form.

The most extensive database for high-energy photon spectral indices $\alpha_h$ in GRBs is for the CGRO EGRET and Comptel bursts. The EGRET $\alpha_h$ index distribution (e.g. Dingus 1995) is constituted by a handful of sources with indices scattered in the range $2 \lesssim \alpha_h \lesssim 3.7$. Of these, EGRET spark chamber detections were concentrated in the index range $\alpha_h \lesssim 2.8$, as tabulated in Baring (2006). One of the flattest EGRET burst spectra was for GRB 930131, with an index $\alpha_h \approx 2$, which corresponds to the indication of $\lambda/r_g \lesssim 10$.
from Fig. 2 (or almost luminal, but not superluminal shocks) if a synchrotron or inverse Compton cooling model is adopted. The CGRO BATSE $\alpha_h$ index distribution (Preece, et al. 2000) is similarly broad, but with $1.5 \lesssim \alpha_h \lesssim 3.5$ and far greater statistics. The recent Fermi detection (Abdo, et al. 2009a) of GRB 080916c in both the GBM and LAT instruments offered a high energy index of $\alpha_h \sim 2.2$ (marked in Fig. 2) in its most luminous epochs, and a generally steeper spectrum at other times. Accordingly, observationally, shock acceleration models must accommodate a radiation spectral index in the range $2 \lesssim \alpha_h \lesssim 4$ in order to be viable. Moreover, they must reasonably account for the spectral variability identified in GRB 080916c, i.e. fluctuating $\alpha_h$ values. This connects to a new development afforded by the refined sensitivity for spectroscopy of Fermi: spectral evolutionary studies in temporal sub-intervals are now a reality, providing a boon for model diagnostics and a honing of the burst paradigm.

Fig. 2 displays photon indices for electron synchrotron emission in strongly cooling scenarios following shock acceleration, where $\alpha_h = (\sigma+2)/2$. It is clear that the flattest spectral epochs for GRB 080916c are best described by highly-oblique, mildly-relativistic shocks, but not quasi-perpendicular ($\Theta_{\text{Bf1}} \gtrsim 70^\circ$) superluminal ones. This can also be inferred for the time-integrated spectral behavior of the EGRET burst GRB 910503 (see Baring, 2006). In contrast, flat-spectrum EGRET bursts GRB 930131 and GRB 950425 with $\alpha_h \lesssim 2$ cannot correspond to superluminal acceleration regimes if radiative cooling is rampant, but demand subluminal shocks with moderate to strong turbulence therein, i.e. $\lambda/r_g \sim 3 - 10$. Other EGRET bursts such as GRB 910601 and GRB 990123 (again see Baring 2006 for tabulated indices), and some sub-intervals in the Fermi dataset (Abdo, et al. 2009a) for GRB 080916c exhibit indices $\alpha_h > 2.5$. From Fig. 2, these bursts can be consistent with acceleration at mildly superluminal shocks in the $60^\circ - 70^\circ$ obliquity range, but only if the scattering is strong, i.e. $\lambda/r_g \lesssim 3 - 10$. No bursts have so far evinced extended power-law spectra flatter than $\alpha_h \approx 1.95$ above the the $\nu - F_{\nu}$ peak (the possibility of additional high energy components above 100 MeV in GRB 940217 [Hurley, et al. 1994], GRB 941017 [Gonzalez, et al. 2003] and more recently GRB 090902b [Abdo, et al. 2009c], is a separate issue), absolving the need for acceleration in shocks with extremely low turbulence, i.e. $\lambda/r_g \gtrsim 10^2$ regimes. This is fortunate, since such shocks are inherently inefficient accelerators. Moreover, the generation of field turbulence is a natural part of dissipation in shocks, so that nearly laminar fields are not expected. Field structures that are devoid of fluctuations are never observed in in situ magnetometer measurements at heliospheric shocks (e.g. Baring et al. 1997, and references therein). Note that moderate field obliquities are quite plausible in mildly-relativistic internal shocks, contrasting ultra-relativistic external GRB shocks, which are necessarily quasi-perpendicular ($\Theta_{\text{Bf1}} \approx 90^\circ$) due to the Lorentz transformation of circumburst fields.
These inferences are predicated on the presumption of efficient cooling in
the burst prompt emission zone. This must operate over a significant range of
electron momenta, since cooling breaks, by an index of $\Delta \alpha_h = 1/2$, are not
observed above 1 MeV in burst emission. For example, if the spectra spanning
the range 1 MeV – 10 GeV in GRB 080916c correspond to a cooling-
dominated contribution, the acceleration must operate in short, impulsive pe-
riods, followed by long cooling epochs that permit the electrons to decline in
momentum by a factor of $10^2$ or so. Then the cooling epochs should possess
durations of around 4 orders of magnitude longer than the impulsive acceleration epochs. This is a significant constraint on cooling scenarios within the
internal shock model (Baring 2009). The alternative of uncooled synchrotron
emission yields a photon differential spectral index given by $\alpha_h = (\sigma + 1)/2$
above the $\nu - F_\nu$ peak. Then the injected distribution must have an index $\sigma$
higher than that for cooling models by unity, in order to match the burst
observations. Specifically, the EGRET GRB index range $2 \lesssim \alpha_h \lesssim 3.7$
maps over to $3 \lesssim \sigma \lesssim 6.4$. This is a profound difference in that it pushes the viable
shock parameter space into the superluminal range, i.e. at higher field obliqui-
ties, and Bohm-limited diffusion is observationally excluded. In addition, for
the less popular uncooled hadronic models, the photon and particle indices
trace each other, i.e. $\alpha_h = \sigma$, and a similar conclusion that the environment
is restricted to modestly superluminal oblique shocks is derived.

It must be emphasized that the spectral index array in Fig. 2 is quite repre-
sentative of the range and parametric behavior for general mildly-relativistic
shocks. While the subluminal/superluminal obliquity boundary varies with $\beta_{1x}$, the morphology of the index curves, their trends with $\lambda/r_g$, and their
rapid transition to large indices when crossing to the superluminal domain
remain qualitatively the same for shock speeds in the range $0.1 \lesssim \beta_{1x} \lesssim 0.9$.

4 Conclusion

This paper has explored constraints imposed on the parameter space for
diffusive acceleration at relativistic shocks by prompt emission observations
in gamma-ray burst. The simulation results presented showcase the non-
universality of the index of non-thermal particles, spawned by a range of
shock obliquities and the varied character of hydromagnetic turbulence in
their environs. This non-universality poses no problem for modeling GRB
high-energy power-law indices $\alpha_h$. The observations generally constrain the
shock parameter space to oblique, subluminal or highly-turbulent superlumi-
nal shocks not far the Bohm diffusion limit, i.e. $\lambda/r_g \lesssim 10$. This presumes
rapidly cooling synchrotron or inverse Compton emission scenarios. If cool-
ing arises on timescales exceeding those pertinent for acceleration, then the
acceleration must occur in mildly superluminal, turbulent shocks; subluminal
shocks produce particle distributions too flat to accommodate the observed spectral indices. The high photon count detections of the long duration GRB 080916c and the short burst GRB 090510 in both Fermi’s GBM and LAT telescopes has afforded a new opportunity to constrain shock acceleration parameters in temporal sub-intervals. The prospect of a number of similar platinum standard, broad-band GRB detections by Fermi that permit time-dependent spectroscopy should hone our understanding of the connection between shock acceleration and prompt emission.

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