PAIR PRODUCTION ABSORPTION TROUGHS IN GAMMA-RAY BURST SPECTRA: A POTENTIAL DISTANCE DISCRIMINATOR

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1 INTRODUCTION

High-energy gamma rays have been observed for six gamma-ray burst (GRB) sources by the EGRET experiment on board the Compton Gamma Ray Observatory. Most conspicuous among these observations is the emission of an 18 GeV photon by the GRB 940217 burst (Hurley et al. 1994). These detections occurred during the first 5 yr of the mission, when the EGRET spark chamber gas level was not severely depleted, and, taking into account the instrumental field of view, they indicate that emission in the 1 MeV–10 GeV range is probably common among bursts, if not universal. One implication of GRB observability at energies around or above 1 MeV is that, at these energies, two-photon pair production (\(\gamma\gamma \rightarrow e^+e^-\)) is not producing any significant spectral attenuation in the source. Attenuation by pair creation in the context of GRBs was first explored by Schmidt (1978). He assumed that a typical burst produced quasi-isotropic radiation and concluded at the time that the detection of photons around 1 MeV limited bursts to distances less than a few kpc, since the optical depth scales as the square of the distance to the burst.

The observation by EGRET of emission above 100 MeV has been exploited to extend the energy range and the lower portion of the EGRET domain into which a burst may be expected to emit. The relative paucity of emission detected below 10 keV in a typical burst produced quasi-isotropic radiation and conclusions based on the assumption of a power-law burst spectrum would be misleading.

ABSTRACT

In order to explain the emergence of a high-energy continuum in gamma-ray bursts detected by EGRET, relativistic bulk motion with large Lorentz factors has recently been inferred for these sources regardless of whether they are of Galactic or cosmological origin. This conclusion results from calculations of internal pair production opacities in bursts that usually assume an infinite power-law source spectrum for simplicity, an approximation that is quite adequate for some bursts detected by EGRET. However, for a given bulk Lorentz factor \(\Gamma\), photons above the EGRET range can potentially interact with sub-MeV photons in such opacity calculations. Hence it is essential to accurately address the spectral curvature in bursts seen by BATSE and also treat the X-ray paucity that is inferred from low-energy fluxes observed in the X-ray band. In this paper we present the major properties induced in photon-photon opacity considerations by such spectral curvature. The observed spectral breaks around 1 MeV turn out to be irrelevant to opacity in cosmological bursts, but they are crucial to estimates of source transparency in the 1 GeV–1 TeV range for sources located in the Galactic halo.

We find that broad absorption troughs can arise at these energies for suitable bulk motion parameters \(\Gamma\). Such troughs are probably an unambiguous signature of a Galactic halo population and if observed by experiments such as Whipple, MILAGRO, and GLAST, would provide powerful evidence that such bursts are not at cosmological distances.

Subject headings: gamma-rays: bursts — gamma rays: theory — radiation mechanisms: nonthermal — relativity

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of the 1 GeV–1 TeV range, with transparency returning in the super-TeV range, resulting in the appearance of distinctive broad absorption troughs. Such features may provide a unique identifier for bursts in halo locales, so that current and future ground-based initiatives such as Whipple and the Multi-institutional Los Alamos Gamma-Ray Observatory (MILAGRO), and space missions such as the Gamma-Ray Large Area Space Telescope (GLAST), may play a key role in determining the distance scale for GRBs.

2. \( \gamma \gamma \) ATTENUATION AND SPECTRAL CURVATURE

In assessing the role of two-photon pair production in burst spectral attenuation, the interactions of photons created only within the emission region are considered here. Recent authors have invoked relativistic beaming in sources when superseding Schmidt’s (1978) early work. This hypothesis builds on the property that \( \gamma \gamma \rightarrow e^+ e^- \) has a threshold energy \( E_t \) that is strongly dependent on the angle \( \theta \) between the photon directions: \( E_t > 2m_e c^2/[1 - \cos \theta] \) \( E_t \) for target photons of energy \( E_t \). Hence, radiation beaming associated with relativistic bulk motion of the underlying medium can dramatically reduce the optical depth \( \tau_{\gamma \gamma} \), in sources at enormous distances from earth, suppressing gamma-ray spectral attenuation turnovers and blueshifting them out of the observed spectral range. The simplest picture of relativistic beaming has “blobs” of material moving with a bulk Lorentz factor \( \Gamma \) more or less toward the observer, and having an angular “extent” \( \sim 1/\Gamma \) (Krolik & Pier 1991; Baring 1993; Baring & Harding 1993). These works assumed an infinite-power-law spectrum \( n(\epsilon) = n_\epsilon \epsilon^{-\alpha} \), where \( \epsilon \) is the photon energy in units of \( m_e c^2 \), for which the optical depth to pair creation assumes the form \( \tau_{\gamma \gamma} \propto \epsilon^{-1/\Gamma^2} \) for \( \Gamma \gg 1 \).

Approximating the source spectrum photon by an infinite power law is expedient, however, most bursts detected by BATSE show significant spectral curvature in the 30–500 keV range (e.g., Band et al. 1993). Furthermore, BATSE sees MeV-type (i.e., 500 keV–2 MeV) spectral curvature with significant frequency in bright bursts; see Schaefer et al. (1992) for an analysis of a brightness-selected sample from early in the BATSE era. EGRET observes three of the Schaefer et al. sources with such “high-energy” breaks (Schneid et al. 1992; Kwok et al. 1993), and later EGRET bursts also exhibit “MeV-type breaks”—for relevant parameters, see Table 1. Hence, EGRET detections seem correlated with spectral breaks at the upper end of the BATSE energy range, which is probably a selection effect for the observability of bursts by EGRET: GRBs with breaks at higher energies tend to be more luminous in the super-MeV range. Whether bursts with breaks at MeV energies are a class of objects distinct from the majority that turnover at lower energies remains to be seen. The MeV-type breaks and those generally seen at lower energies in the BATSE data for many GRB spectra could, in principle, reduce the opacity of potential TeV emission from these sources, so it is important to generalize the pair production opacity/relativistic beaming analysis to include the effects of spectral curvature.

The effects of a depletion of low-energy photons in the BATSE range relative to the EGRET quasi–power-law spectra can quickly be determined by taking the simplest approximation to spectral curvature, namely, a power law broken at a dimensionless energy \( \epsilon_B = (E_B/0.511 \text{ MeV}) \) with a low-energy cutoff at \( \epsilon_c \):

### Table 1

| GRB          | \( E_B \) (MEV) | \( \alpha_L \) | \( \alpha_S \) | \( \alpha_H \) |
|--------------|----------------|----------------|----------------|---------------|
| 910503........ | 0.4 ± 0.2      | 0.7 ± 0.1      | 2.1            | 2.2 ± 0.2     |
| 910601........ | 0.6 ± 0.2      | 1.0 ± 0.1      | steep          | 3.7 ± 0.2     |
| 910814........ | 1.2 ± 0.1      | 0.9 ± 0.1      | steep          | 2.8 ± 0.2     |
| 930131........ | 0.7 ± 0.1      | 1.2 ± 0.1      | 2.5            | 2.0 ± 0.2     |
| 940217........ | 0.8 ± 0.1      | 1.2 ± 0.2      | ...            | 2.5 ± 0.2     |

Note.—The values of the break energy \( E_B \) and the spectral index below \( \alpha_L \) and above \( \alpha_H \), if the break for five of the six bursts observed by both BATSE and EGRET. For the first three bursts, the BATSE parameters are taken from Band et al. (1993, the Band model fit; the “steep” entries indicate the inability of the fit to pin down the high-energy tail), while the remaining BATSE data were obtained for GRB 930131 from Kouveliotou et al. (1994) and for GRB 940217 from Hurley et al. (1994, who quote no BATSE result for \( \alpha_L \)). The high-energy spectral indices \( \alpha_H \) as determined by EGRET are from Schneid et al. (1992; GRB 910503) and Kwok et al. (1993; GRBs 910601 and 910814), Sommer et al. (1994; GRB 930131), and Hurley et al. (1994; GRB 940217).
A remarkable feature of equation (2) is that the optical depth is no longer necessarily a monotonically increasing function of energy $E$. The parameters $\eta_h$ and $\eta_c$ govern the importance, or otherwise, of spectral curvature effects. Clearly, if either $\eta_h$ or $\eta_c$ (in $m_c e^2$) is low enough or $\eta_h = 1$, then the pure power-law result emerges from equation (2) and curvature effects are negligible. Such a situation might then be expected for cosmological bursts. Conversely, if $\eta_h$ or $\eta_c$ exceed unity, the shape of the BATSE spectrum becomes crucial to optical depth estimates. The spectra in equation (1) were attenuated using the optical depth in equation (2), specifically via an exponential factor $\exp(-\tau_{\nu})$, for fluxes and spectra typical of bright GRBs (e.g., Table 1); the emergent spectra are depicted in Figure 1. The results for the cosmological cases are noticeably different; the input broken power law is modified (as expected intuitively) by a quasi-exponential turnover at an energy that is an increasing function of the bulk Lorentz factor $\Gamma$ of the expansion that generates the radiation. If $\Gamma$ were chosen large enough to permit emission out to TeV energies, the spectra would suffer attenuation due to the external supply of cosmological infrared background photons (Stecker & De Jager 1996; Mannheim, Hartmann, & Funk 1996). Note that opacity skin effects can sometimes render the exponential factor $\exp(-\tau_{\nu})$ a poor descriptor of attenuation, with $1/(1 + \tau_{\nu})$ perhaps being an improvement, leading to broken power laws rather than exponential turnovers. Such alternatives, which are model-dependent, do not qualitatively affect the conclusions drawn here and are discussed in BH97.

The Galactic halo case in Figure 1, where typically $\eta_h \gtrsim 1$, exhibits remarkably different behavior: broad absorption features occur in the 1 GeV–1 TeV range, depending on the choice of source $\Gamma$. The presence of these notable troughs, which become more pronounced as $\Gamma$ decreases, results from the nonmonotonic behavior of the optical depth with energy: $\tau_{\nu}$ drops below unity around the TeV range because of the “depleted supply” of interacting photons in the low-energy BATSE portion of the spectrum. These distinctive features arise only for large spectral breaks (i.e., $\delta \alpha = |\alpha_h - \alpha_i| \gtrsim 1.3$), and also MeV-type break energies; a reduction of the severity or energy of the break pushes the attenuation towards the more familiar exponential turnovers depicted in Figure 1. The appearance of the troughs is most strongly dependent on the size of $\delta \alpha$ and on $\alpha_i$ being not too large. Consequently, from the data in Table 1, it appears that GRBs 910601 and 910814 would be the strongest candidates for producing features like those exhibited in Figure 1. The other EGRET bursts are in a marginal regime of parameter space; attenuation results for them are discussed in BH97. Note that the structure on the low-energy end of the troughs is a product of the sharp spectral breaks used and is smoothed out (BH97) for more realistic spectral curvature.

Attenuation of spectra appropriate to the burst GRB 910814 are depicted in Figure 2 for different $\Gamma$. The case where there is no low-energy cutoff yields an extremely broad trough, which is more reminiscent of a “shelf.” Such behavior differs from the halo cases in Figure 1 because here the source spectra are somewhat steeper, producing much broader troughs; the result would be an improbability of observing sources like GRB 910814 at TeV energies when no low-energy cutoff is present. In contrast, when a spectral cutoff is present at 5 keV in Figure 2 (which is below the threshold of BATSE sensitivity), mimicking the X-ray paucity of bursts (Epstein 1986; actually this is a paucity of energy in X-rays, so that it may be better described by a significant spectral break), the supply of interacting photons is further depleted, the troughs narrow, and TeV emission reappears. This property clearly
underlines the importance of the relationship between the 10 GeV–1 TeV and the soft X-ray portions of the GRB spectrum, correlations which can only be analyzed using broad band observations of bursts. Note that the highest EGRET spectral point for GRB 910814 in Figure 2 indicates that the bulk Lorentz factor is constrained to $\Gamma \gtrsim 20$.

The array of spectral shapes depicted in Figures 1 and 2 indicates that a diversity of such forms must be anticipated in GRBs, with troughs, shelves, and turnovers, depending on source spectral parameters (see BH97). The reason for the appearance of troughs in the Galactic halo case but not for cosmological distances stems from the much higher photon densities inferred in cosmological sources for a given flux at earth, for which photon-photon collisions primarily involve photons well above 1 MeV, and spectral curvature in the BATSE range is irrelevant. Note that the model-dependent details of pair cascading have been neglected here; these are discussed in BH97.

3. IMPLICATIONS

The importance of the spectral attenuation results presented here is immediately apparent. The absorption troughs in Figures 1 and 2 cannot be produced for large source distances and are unambiguous markers of a Galactic halo burst population; they are consequently a potentially powerful observational diagnostic. Observations by the air Cerenkov detectors Whipple and MILAGRO (a new water tank experiment) at the 300 GeV–5 TeV range, and perhaps even HEGRA at higher energies, combined with a probing of the 100 MeV–100 GeV range by future space instrumentation such as GLAST (a spark chamber experiment) could confirm or deny the existence of such absorption features. Note that the observation of apparently sharp cutoffs would not distinguish between cosmological or Galactic burst hypotheses. The current Whipple sensitivity threshold (Connaughton et al. 1995) is not sufficiently constraining, so future generations of experimentation will be required to assess whether or not GeV–TeV troughs are present in GRB spectra. Having five times the field of view and around 10 times the sensitivity of EGRET and, therefore, the potential to detect dozens of bright bursts per year, the proposed GLAST mission (Michelson 1996) might be expected to make significant inroads into this problem.

The shape and position of these prominent features are strongly dependent on the spectral slopes and fluxes in the BATSE and EGRET ranges and, even more interestingly, on the contributions to the source flux from below 10 keV. Hence, coupled X-ray and soft and hard gamma-ray observations are clearly warranted, an exciting challenge to the astronomy and GRB communities. The strong and well-defined correlations between the width and shape of the troughs and the spectral curvature below 10 MeV act as clear markers of the pair production attenuation analysis discussed here, and are unlikely to be replicated in detail by alternative, multicomponent models (e.g., Katz 1994; Mészáros & Rees 1994) of hard gamma-ray emission or from opacity due to external background fields of radiation (such attenuation is generally above 100 GeV; Stecker & De Jager 1996; Mannheim et al. 1996). In summary, this paper presents a patently powerful spectral diagnostic in the super-GeV range that can provide enticing prospects for solving the problem of GRB location.

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REFERENCES

Band, D., et al. 1993, ApJ, 413, 281
Baring, M. G. 1993, ApJ, 418, 391
———. 1994, ApJS, 90, 899
Baring, M. G., & Harding, A. K. 1993, in Proc. 23d Int. Cosmic-Ray Conf. (Calgary), 53
———. 1996, in AIP Conf. Proc. 384, Gamma-Ray Bursts, ed. C. Kouveliotou, M. F. Briggs, & G. J. Fishman (New York: AIP), 724
———. 1997, in preparation (BH97)
Connaughton, V., et al. 1995, in Proc. 24th Int. Cosmic-Ray Conf. (Rome), 2, 96
Epstein, R. I. 1986, in Radiation Hydrodynamics in Stars and Compact Objects, ed. K. H. Winkler & D. Mihalas (Heidelberg: Springer), 305
Fenimore, E. E., Epstein, R. I., & Ho, C. 1992, in AIP Conf. Proc. 265, Gamma-Ray Bursts, ed. W. S. Paciesas & G. J. Fishman (New York: AIP), 158
Gould, R. J., & Schreder, G. P. 1967, Phys. Rev. 155, 1404
Harding, A. K. 1994, in AIP Conf. Proc. 304, 2d Compton Symposium, ed. C. Fichtel, N. Gehrels, & J. Norris (New York: AIP), 30
Hurley, K., et al. 1994, Nature, 372, 652
Katz, J. 1994, ApJ, 432, L27
Kouveliotou, C., et al. 1994, ApJ, 422, L59
Krolik, J. H., & Pier, E. A. 1991, ApJ, 373, 277
Kwok, P. W., et al. 1993, in AIP Conf. Proc. 280, Compton Gamma Ray Observatory, ed. M. Friedlander, N. Gehrels, & D. Macomb (New York: AIP), 855
Mannheim, K., Hartmann, D., & Funk, B. 1996, ApJ, 467, 532
Meegan, C., et al. 1992, Nature, 355, 143
———. 1996, ApJS, 106, 65
Michelson, P. F. 1996, Proc. SPIE 2806, 31
Mészáros, P., & Rees, M. J. 1994, MNRAS, 269, L41
Schaefer, B. E., et al. 1992, ApJ, 393, L51
Schmidt, W. K. H. 1978, Nature, 271, 525
Schneid, E. J. 1992, A&A, 255, L13
Sommer, M., et al. 1994, ApJ, 422, L63
Stecker, F. W., & De Jager, O. C. 1996, Space Sci. Rev., 75, 401

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