Prompt and Delayed High-Energy Emission from Cosmological Gamma-Ray Bursts

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Abstract

In the cosmological blast-wave model for gamma ray bursts (GRBs), high energy ($\gtrsim 10$ GeV) $\gamma$ rays are produced either through Compton scattering of soft photons by ultrarelativistic electrons, or as a consequence of the acceleration of protons to ultrahigh energies. We describe the spectral and temporal characteristics of high energy $\gamma$ rays produced by both mechanisms, and discuss how these processes can be distinguished through observations with low-threshold Čerenkov telescopes or GLAST. We propose that Compton scattering of starlight photons by blast wave electrons can produce delayed flares of GeV – TeV radiation.

1 Introduction

The blast-wave model has met with considerable success in explaining the X-ray, optical and radio afterglows of GRBs [6]. The evolving blast wave accelerates particles to ultrarelativistic energies and has been suggested as the source of ultrahigh-energy cosmic rays (UHECRs) [10,8]. GeV – TeV photon production, due primarily to proton synchrotron radiation from UHECR acceleration in GRBs during the afterglow phases, has recently been predicted [9,1]. A large Compton luminosity when relativistic electrons scatter soft photons is expected as well. One source of seed photons is the electron synchrotron radiation, and the synchrotron self Compton (SSC) process has been calculated by [2]. External soft photon sources could also be important in the Compton scattering process. Models for the GRB origin such as the hyper-nova/collapsar [7,11] scenario suggest that the sources of GRBs are associated with star-forming regions and might thus be embedded in a starlight radiation field. Here we examine the Compton scattering of starlight by relativistic electrons in the blast wave.
We compare high energy $\gamma$-ray emissions due to SSC and SSL (Scattered StarLight) processes, which can be estimated by comparing the comoving blast-wave frame energy densities $u_{SL}'$ and $u_{sy}'$ of starlight and synchrotron photons, respectively. Knowledge of the peak energy of the seed photon spectrum, which determines whether Compton scattering is suppressed due to Klein-Nishina effects, is important for this comparison. The relativistic electrons are assumed to be distributed according to a power-law with index $\gtrsim 3$ and a low-energy cutoff $\gamma_{e,\text{min}} = \xi_e (m_p/m_e) \Gamma$ [5], where $\xi_e = 0.1 \xi_{e,-1}$ is an electron equipartition factor, and $\Gamma = 300 \Gamma_{300}$ is the bulk Lorentz factor of the blast wave. The magnetic field is $H = \sqrt{8\pi r m_p c^2 n_0 \xi_H \Gamma}$, where $r = 10 r_1$ is the shock compression ratio, $n_0$ is the number density of external matter, assumed uniform, and $\xi_H = 10^{-6} \xi_{H,-6}$ is a magnetic-field equipartition factor. A value of $\xi_H \sim 10^{-6}$ is required to produce synchrotron spectra resembling observed spectra in the prompt phase of GRBs [2].

### 2.1 Synchrotron and SSC Processes

The peak photon energy of the synchrotron spectrum is $\epsilon_{sy}' \simeq 10^{-4} \Gamma_{300}^{3} n_0^{1/2} q_{-4}$, where $q = \sqrt{r_1 \xi_H \xi_e^2} = 10^{-4} q_{-4}$ is a combined equipartition factor. The energy density of the synchrotron radiation field may be estimated using $u_{sy}' \simeq \tau_T^2 \gamma_{e,\text{min}}^2 u_H'$, where $\tau_T$ is the radial Thomson depth of the blast wave. Specifying the width of the shell, $\Delta x' \simeq x' / \Gamma$, at the deceleration radius, we find

$$u_{sy}' \text{[erg cm}^{-3}] \simeq 7.3 \cdot 10^{-6} r_1^2 n_0^{5/3} \xi_{H,-6} E_{52}^{1/3} \xi_{e,-1}^2 \Gamma_{300}^{10/3},$$

where $E_0 = 10^{52} E_{52}$ erg is the kinetic energy of the blast wave. SSC scattering can occur efficiently in the Thomson regime if $\xi_{e,-1} \Gamma_{300} n_0^{1/2} q_{-4} \lesssim 1$. In this case, the SSC spectrum in the observer’s frame peaks at

$$\epsilon_{\text{SSC}} = h\nu_{\text{SSC}} / m_e c^2 \simeq 10^8 \Gamma_{300}^6 \xi_{e,-1}^2 n_0^{1/2} q_{-4} / (1 + z),$$

which cannot exceed $\epsilon_{\text{IC,max}} \simeq 1.6 \cdot 10^7 \xi_{e,-1} \Gamma_{300}^2 / (1 + z)$.

### 2.2 Scattered Starlight

We assume that the blast wave approaches a star of luminosity $L_* = l L_\odot$ at a distance $d = d_{15}$ cm from a given point within the blast wave. Then the
energy density of the stellar radiation field in the blast-wave frame is

\[ u'_{\text{SL}}[\text{erg cm}^{-3}] \approx \frac{1.3 \cdot 10^{-3} / \Gamma_{300}^2}{d_{15}^2} \tag{3} \]

By comparing eqs. (1) and (3), we see that \( u'_{\text{SL}} \) dominates \( u'_{\text{sy}} \) when \( d_{15} \lesssim d_{\text{SSL}} \equiv 131^{1/2} \Gamma_{300}^{-2/3} r_1^{-1} n_0^{-5/6} e^{-1/2} \xi_{H, -6} \xi_{e, -1} E_{52}^{-1/6} \).

If the starlight spectrum is approximated by a thermal blackbody of temperature \( T_0[\text{eV}] \), then this spectrum peaks in the comoving blast-wave frame at
dimensionless photon energy \( \epsilon'_{\text{SL}} \approx 1.6 \cdot 10^{-3} \Gamma_{300} T_0 \). Compton scattering can occur in the Thomson regime if \( \Gamma_{300}^2 \xi_{e, -1} T_0 \lesssim 10^{-2} \), indicating that the SSL process becomes efficient only if \( \Gamma \lesssim 30 (\xi_{e, -1} T_0)^{-1/2} \). This can be realized in dirty fireballs [4] or in the later afterglow phase of blast-wave deceleration. When the above condition is satisfied, the SSL spectrum in the observer’s frame peaks at

\[ \epsilon_{\text{SSL}} \approx 1.5 \cdot 10^5 \Gamma_{300}^4 T_0 \xi_{e, -1}^2 / (1 + z), \tag{4} \]

where \( \Gamma_{300} = \Gamma / 30 \). The SSL component can dominate once scattering occurs primarily in the Thomson regime, at which point it is likely to be the dominant electron radiation mechanism in the 10 – 100 GeV regime.

The minimum duration of flares from the SSL process is \( \Delta t_{\text{min}} \approx d / (\Gamma^2 c) \approx 40 d_{15} / \Gamma_{300}^2 \) s. The fraction of energy in GeV – TeV photons produced by the SSL mechanism rather than through other processes is roughly given by \([d_{\text{SSL}}/(x_{bw}/\Gamma)]^2\), which represents the fraction of the observable blast wave area where \( u'_{\text{SL}} \) dominates \( u'_{\text{sy}} \). The term \( x_{bw} \) is the distance of the blast wave from the explosion site. Čerenkov telescopes with threshold energies below \( \sim 100 \) GeV and the planned GLAST satellite might be able to detect the predicted SSL radiation from nearby GRBs if they are indeed associated with star-forming regions.

### 3 Comparison with Gamma Rays from Hadronic Processes

The high energy \( \gamma \)-ray signatures of UHECR acceleration in GRB blast waves have been investigated in detail in [1]. If protons are accelerated efficiently in GRB blast waves, the spectrum in the \( \sim 10 – 100 \) GeV range is expected to be dominated by a hard power-law with \( \nu F_{\nu} \propto \nu^{+0.5} \) due to proton synchrotron radiation. Since protons are expected to cool inefficiently, while electrons suffer strong radiative cooling, the temporal decay of the proton synchrotron radiation is slower than for the synchrotron component component. Let \( g \) be
the index parametrizing the deceleration and thereby the radiative regime of the blast wave, then both components decay as $F_{\nu}(t) \propto t^{-\chi}$, but with different temporal indices. For synchrotron radiation from cooling electrons, $\chi_{sy} = (4g-2)/(1+2g)$, while for uncooled synchrotron radiation from UHECR, $\chi_{p,sy} = (4g-3)/(1+2g)$. The temporal decay of the SSC radiation is more complicated, because scattering in the Klein-Nishina is important. Comparison of decay observations over a large range of photon energies with model calculations are necessary to accurately discriminate between the various processes. The SSL radiation can be distinguished from the SSC and the hadronic $\gamma$-ray emission by its rapid variability and by the flares it produces in the GeV range. Observations of flares of GeV - TeV radiation would support the hypothesis that GRBs occur within stellar associations and star-forming regions.

**References**

[1] Böttcher, M., & Dermer, C. D., 1998, ApJL, 499, L131
[2] Chiang, J., & Dermer, C. D. 1998, ApJ, in press (astro-ph/9803339)
[3] Dermer, C. D., & Schlickeiser, R. 1994, ApJS, 90, 945
[4] Dermer, C. D., Chiang, J., & Böttcher, M., 1999, ApJ, 513, in press
[5] Mészáros, P., Rees M. J., & Papathanassiou, H. 1994, ApJ, 432, 181
[6] Mészáros, P., Rees, M. J., & Wijers, R. A. M. J., 1997, ApJ, 499, 301
[7] Paczyński, B., 1998, ApJL, 494, L45
[8] Vietri, M. 1995, ApJ, 453, 883
[9] Vietri, M. 1997, PRL 78, 23, 4328
[10] Waxman, E. 1995, PRL, 75, 386
[11] Woosley, S. E., 1993, ApJ, 405, 273