GLAST PROSPECTS FOR SWIFT-ERA AFTERGLOWS

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ABSTRACT

We calculate the GeV spectra of gamma-ray burst afterglows produced by inverse Compton scattering of these objects’ sub-MeV emission. We improve on earlier treatments by using refined afterglow parameters and new model developments motivated by recent Swift observations. We present time-dependent GeV spectra for standard, constant-parameter models, as well as for models with energy injection and with time-varying parameters, for a range of burst parameters. We evaluate the limiting redshift to which such afterglows can be detected by the GLAST Large Area Telescope, as well as by AGILE.

Subject headings: gamma rays: bursts — radiation mechanisms: nonthermal

1. INTRODUCTION

Gamma-ray burst (GRB) afterglow observations from X-rays to radio are generally well described by an external-shock model (see, e.g., Mészáros 2006 for a recent review). However, model fits to the data still leave uncertainties in some of the parameters of the basic external-shock model, and the bolometric luminosity depends on the poorly known GeV range of the spectrum. The Gamma-Ray Large Area Space Telescope (GLAST; MeEnery & Ritz 2006) is expected to be launched at the end of 2007. Its Large Area Telescope (LAT) covers the energy range from 20 MeV to 300 GeV, while the GLAST Burst Monitor (GBM) covers the range from 8 keV to 25 MeV. The effective area of the LAT is about 7 times larger than that of the earlier EGRET experiment at GeV energies. AGILE³ was successfully launched on 2007 April 23, with an energy range of 30 MeV to 50 GeV (Tavani et al. 2006). It is hoped that the higher photon statistics at GeV energies of GLAST and AGILE will lead to tighter constraints on the burst parameters and an improved understanding of the GeV afterglow spectra.

GLAST may also be able to test recent developments in the understanding of GRB afterglows, motivated by observations with the Swift satellite (e.g., Nousek et al. 2006; Zhang et al. 2006; Fox & Mészáros 2006; Zhang 2007). One such development is the presence of a shallow decay phase in the X-ray afterglow, which may be due to refreshed shocks or a late energy injection (e.g., Zhang et al. 2006) or, alternatively, may be due to a change in the shock parameters over time (e.g., Ioka et al. 2006). We investigate here the effects of such new features on the expected GeV spectrum.

Another question of great interest is how far GLAST can detect the MeV-to-GeV emission from such bursts, both in the basic model and the case in which new features such as the above are present. This requires a detailed calculation of the GeV spectrum as a function of time, with allowance for the changes in dynamics implied by the injection, time variability, etc. The most conservative and widely considered mechanism for producing photons in this range is inverse Compton scattering (Panaitescu & Mészáros 1998; Totani 1998; Wei & Lu 1998; Chiang & Dermer 1999; Panaitescu & Kumar 2000; Sari & Esin 2001; Zhang & Mészáros 2001; Wang et al. 2001, 2006; Wei & Fan 2007; Fan et al. 2007; Galli & Piro 2007). Another potential mechanism is hadronic cascades following proton acceleration (Böttcher & Dermer 1998; Zhang & Mészáros 2001; Fragile et al. 2004; Gupta & Zhang 2007). This mechanism is less well constrained, depending on the efficiency of proton acceleration; it may be important in the prompt phase, but its parameter regime is small and generally outside the range of afterglow parameter fits (Zhang & Mészáros 2001), so it is not considered here. The maximum distance to which GLAST could detect a GRB afterglow was discussed in Zhang & Mészáros (2001) for the basic standard model, using a simplified analytical broken power law approximation to the IC spectrum. This resulted in an IC-to-synchrotron peak flux ratio that is overestimated by a factor of ~10, compared with a more accurate calculation, as we discuss in this paper. The usefulness of this ratio is that it allows simple predictions for the detectability in the GeV range based on lower energy measurements. Here we discuss the validity of the simple analytical approximations compared with more accurate numerical calculations of afterglow spectra at GeV energies.

In § 2, we describe the afterglow synchrotron-IC model used for the numerical computations, a comparison between numerical and analytical approximations being given in the Appendix. In § 3, we present both numerical IC spectra and their appropriate analytical approximations for the basic GRB afterglow model and for extended models including new Swift-motivated elements, such as energy injection or time-varying parameters, and evaluate their detectability as a function of redshift for the GLAST LAT instrument and for AGILE.

2. AFTERGLOW SYNCHROTRON–INVERSE COMPTON SPECTRA AT GeV ENERGIES

The afterglow of a GRB, because of the slowing of the external shock as it encounters the external medium, produces synchrotron radiation in the X-ray–MeV range, which is then inverse Compton upscattered into the GeV–TeV range (Mészáros et al. 1994; Böttcher & Dermer 1998; more specific calculations of the IC GeV range are, e.g., those of Sari & Esin 2001; Zhang & Mészáros 2001; Pe’er & Waxman 2004). We describe the afterglow models, as usual, by the total isotropic energy $E_{52,\text{iso}} = E/(10^{52} \text{ergs})$ (for the case of energy injection, see below), the external density $n$, a jet opening half-angle $\theta$, an electron equipartition parameter $\epsilon_e$, a magnetic equipartition parameter $\epsilon_B$, and an electron energy index $p$. The other parameter of relevance in

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The kinetic energy redshift for detection of GLAST

The thick solid line is the other two models. (GLAST models in the absorption, and the lower curves are with inclusion of this absorption. (c) GLAST sensitivity curves gives the limiting redshift to which bursts can be detected by spectra for the standard model at different epochs: 10^{-2}, 10^{-4}, 10^{-5}, and 10^{-6} s. Above photon energies of Y_{\text{synchrotron-IC}} models is the scattering by defined as the ratio of IC to synchrotron luminosity, usually given

The initial Lorentz factor $\Gamma_0$ of the burst is not needed as a parameter, since in the asymptotic blast wave regime the Lorentz factor follows from the scaling law

$$\Gamma(t) = (17E/1024\pi nm_p c^2 \lambda^2)^{1/8}.$$  

Our numerical calculations of the spectra and fluence curves use the basic synchrotron-IC equations given in Gou et al. (2007), extended now to the GeV range. We also consider in this range the spectral effects of photon-photon opacity, which impose cutoffs depending on the spectrum and density of lower energy photons (Baring & Harding 1997; Lithwick & Sari 2001).

We calculate the synchrotron-IC spectra of three different types of GRB afterglow model and evaluate their detectability with the GLAST LAT and with AGILE. These calculations improve on previous calculations (e.g., Zhang & Mészáros 2001) in several respects. First, in the “standard” afterglow model such as used in Zhang & Mészáros (2001), we use the exact IC spectrum instead of the broken power law approximation, and the peak flux ratio is taken as $F_1$ instead of $F_2$ (see Appendix). Second, we include the entire spectral regime, not just the commonly used $\nu_0 < (\nu_m, \nu_c)$ regimes, where $\nu_0$, $\nu_m$, and $\nu_c$ are the synchrotron self-absorption, injection, and cooling frequencies, respectively (Gou et al. 2007). This ensures that the GRB afterglows evolve through the correct regime at all times. Third, we consider Swift-motivated additions to the standard afterglow model, such as a continued energy injection model and a model with varying afterglow parameters (motivated by the presence of a shallow decay phase and a high apparent radiative efficiency; see, e.g., Mészáros 2006 for a review).

The details of the three models calculated are as follows: (A) A standard afterglow model, with all parameters remaining constant during its evolution (for a detailed description of this model, see Gou et al. 2007). (B) A model with continuous energy injection, which is a widely considered model to explain the shallow decay phase commonly seen in Swift light curves. For this, we assume that the total kinetic energy increases over time as a power law $E \propto t^{1-q}$ before the break time, $t = 10^4$ s, the break time here being defined as when the shallow decay phase ends. Fits to Swift observations indicate a value $q \sim 0.5$ (Zhang et al. 2006).

**Fig. 1.**—(a) Partial-fluence curves (defined as flux integrated between 0.5\tau and \tau) as a function of the observation time \tau since the trigger, for the three GRB afterglow models in the GLAST LAT energy band, at a redshift $z = 0.32$. Thin solid line, standard model (A) (constant energy); dashed line, “energy injection” model (B); dash-dotted line, “evolving parameter” model (C). The LAT sensitivity is shown by the thick solid line. The parameters for the standard model are $E_{32,\text{tot}} = 1$, $\epsilon_e = 0.5$, $\epsilon_B = 0.01$, $p = 2.2$, and $\theta = 0.14$ rad, and the break time when the shallow decay phase ends is at $t = 10^4$ s. Before the break time, $\epsilon_e \propto t^{0.5}$ in the evolving-parameter model and the kinetic energy $E \propto t^{0.5}$ in the energy injection model. After the break time, those parameters will be the same as those in the standard model. (b) Synchrotron and IC spectra for the standard model at different epochs: $10^2$, $10^4$, $10^5$, and $10^6$ s. Above photon energies of $\sim 10^{12}$ eV, the upper spectral curves represent the flux without $\gamma-\gamma$ absorption, and the lower curves are with inclusion of this absorption. (c) Redshift dependence of the partial fluence for the three models above, evaluated at $t \sim 1.1 \times 10^3$ s. The thick solid line is the GLAST sensitivity for an integration time of 550 s (an observing efficiency of 0.5 has been assumed). The intersection of the partial fluence and the sensitivity curves gives the limiting redshift to which bursts can be detected by GLAST for this integration time, which is $z \sim 0.4$ for the standard model and $z \sim 0.22$ for the other two models. (d) Same as (c), but evaluated at $t \sim 2.0 \times 10^4$ s. The thick solid line is the GLAST sensitivity for an integration time of $10^4$ s. The intersection gives a limiting redshift for detection of $z \sim 0.45$ for all three models.

synchrotron-IC models is the scattering $Y$-parameter, which is defined as the ratio of IC to synchrotron luminosity, usually given by

$$Y = (-1 + \sqrt{4 \epsilon_c / \epsilon_B + 1})/2.$$  

The initial Lorentz factor $\Gamma_0$ of the burst is not needed as a parameter, since in the asymptotic blast wave regime the Lorentz factor follows from the scaling law

$$\Gamma(t) = (17E/1024\pi nm_p c^2 \lambda^2)^{1/8}.$$  

\[ \text{Log(Fluence)} \begin{array}{c} \text{(erg/cm²)} \\ \text{Log(Time) (s)} \end{array} \]

\[ \text{Log(Flux)} \begin{array}{c} \text{(erg/s/cm²)} \\ \text{Log(Energy) (eV)} \end{array} \]

\[ \text{Log(Fluence)} \begin{array}{c} \text{(erg/cm²)} \\ \text{Redshift} \end{array} \]

\[ \text{Log(Flux)} \begin{array}{c} \text{(erg/s/cm²)} \\ \text{Redshift} \end{array} \]
(C) An evolving-parameter model, which is an alternative for explaining the shallow decay phase, based on the assumption that the electron equipartition parameter $c_e$ increases with time as $t^n$ (Ioka et al. 2006) before the break time, as in the energy injection model. We assume that all three models have the same parameters at late times, that is, after the break time. Because the flux has to be integrated over the observation time, we set the observation time to be one-half the final time of observation after the trigger (e.g., if the observational data stop at time $t = 10^5$ s, the integration is from $t = 5 \times 10^4$ s to $t = 10^5$ s). This is consistent with the GLAST observation characteristics, as well as those of AGILE, in the point-source observing mode, where, because of Earth occultation, only about 50% of the orbit time is used for burst observation.

To determine the limiting redshift to which a burst can be detected, we calculate the instrumental fluence threshold as in Zhang & Mészáros (2001), using the instrument characteristics of the GLAST LAT and AGILE. For a flux sensitivity $\Phi_{in}$ photons cm$^{-2}$ s$^{-1}$ over an exposure time $T$ and a point source observed over an effective observation time $t_{eff}$ (in seconds) in an energy band centered around a photon energy $E$, the fluence threshold is estimated as $F_{thr} \sim [\Phi_{in}(T/t_{eff})^{1/2}]E_{eff}$, where $\Phi_{in}(T/t_{eff})^{1/2}$ is the sensitivity for the effective observation time $t_{eff}$ because the sensitivity scales as $t_{eff}^{1/2}$ for longer observations, for which the sensitivity is limited by the background. Because of occultations by Earth, the effective observation time $t_{eff}$ is normally $\leq 50\%$ of the total orbit time, $t_{obs}$, for both GLAST and AGILE (or equivalent to the observation time after the burst), namely, $t_{eff} = \eta t_{obs}$, where the observing efficiency $\eta$ is taken to be $\eta = 0.5$. Hereafter, unless otherwise stated, $t$ without a subscript refers to the observation time $t_{obs}$ for simplicity. For GLAST we use the fluence threshold listed in the updated instrument performance documents.$^4$ Considering the integral sensitivity above 100 MeV for LAT to be $\sim 4 \times 10^{-9}$ photons cm$^{-2}$ s$^{-1}$ for an effective observation time of 1 yr in survey mode, the fluence threshold is $1.0 \times 10^{-8}$ ergs cm$^{-2}$ for long-duration observations in this mode. For GRB afterglows, in most cases GLAST will perform a pointed observation rather than a survey-mode observation. In pointed mode, GLAST keeps the GRB position at the center of the LAT field of view for as long as possible, and this improves the sensitivity by a factor of 3–5 (depending on where the GRB lies with respect to the orbital plane—an object that lies at the orbit pole will not be occulted by Earth and can be continuously observed; J. McEnery 2007, private communication). Therefore, taking an improvement factor of 3, the fluence threshold for a GRB observation is $3.4 \times 10^{-9}$ ergs cm$^{-2}$ for a long-duration observation. The short-duration fluence threshold can be defined by the criterion that at least 5 photons are collected and depends on the effective area of the instrument, which is around 6000 cm$^2$ at 400 MeV for LAT, so it is $5.3 \times 10^{-7}$ ergs cm$^{-2}$ (the transition time at which the short- and long-duration sensitivities meet is $2.4 \times 10^4$ s). Compared with the previous estimate of Zhang & Mészáros (2001) for the GLAST sensitivity, the short-duration sensitivity here is roughly the same, but the long-duration sensitivity has changed from $1.2 \times 10^{-9}$ to $3.4 \times 10^{-9}$ ergs cm$^{-2}$, an increase by a factor of 3.

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$^4$ See http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm.
The energy range of AGILE is somewhat lower than that of LAT. Its flux sensitivity above 100 MeV is \( \sim 3 \times 10^{-7} \) photons cm\(^{-2}\) s\(^{-1}\) for a point-source observation over an effective period of 10\(^6\) s (Tavani et al. 2006). Thus, taking an observing efficiency \( \eta = 0.5 \), the fluence threshold can be estimated as \( 3.0 \times 10^{-7} (T/T_{\text{eff}})^{1/2} \times E_{\text{eff}} \approx 1.3 \times 10^{-7} t^{1/2} \) ergs cm\(^{-2}\) at an average energy of 400 MeV, where \( T = 10^6 \) s is the exposure time corresponding to the given sensitivity. This fluence threshold is for a long-duration observation. The fluence threshold for shorter observations can be obtained as above, \( \sim (5/550) \times 400 \) MeV \( \sim 5.8 \times 10^{-6} \) ergs cm\(^{-2}\), where we have taken the effective area for AGILE to be 550 cm\(^2\). In summary, for AGILE the fluence threshold for long observations (i.e., \( t > 1870 \) s) is \( 1.3 \times 10^{-7} t^{1/2} \) ergs cm\(^{-2}\) and that for short observations is \( 5.8 \times 10^{-6} \) ergs cm\(^{-2}\), the transition being at \( \approx 1870 \) s.

### 3. DETECTABILITY OF GRB AFTERGLOWS WITH GLAST AND AGILE

The initial nominal set of parameters for the standard model (model A) used here are the same as for the standard model of Zhang & Mészáros (2001): \( p = 2.2, \epsilon_e = 0.5, \epsilon_B = 0.01, E_{52,\text{iso}} = 1 \), and \( n = 1 \) cm\(^{-3}\). An additional feature is that we also assume a jet opening half-angle \( \theta = 0.14 \) radians, which does not affect the flux at early times. The other parameters are as for model A. For the injection model (B), the kinetic energy is assumed to increase following the relation \( E \propto t^{-q} = t^{0.5} \), where \( q \) is taken to be 0.5 based on fits to Swift observations (Zhang et al. 2006). For the model with evolving parameters (C), we assumed that \( \epsilon_e \) follows the relation \( \epsilon_e \propto t^{0.5} \) (Ioka et al. 2006), the other parameters being the same as for model A. In the alternative models B and C, either the kinetic energy or the electron equipartition parameter starts out with a smaller value than for model A but, at late times, ends up with the same values as in the standard model. The transition time at which the energy injection or the evolution in \( \epsilon_e \) stops is set at \( t = 10^4 \) s.

Figure 1 shows the results for the three models, using the nominal set of parameters. Figure 1a shows the partial fluence, defined here as the energy flux integrated over the time interval \( [t - \Delta t, t] \), as a function of \( t \), where \( t = t_{\text{obs}} \) is the observation time, counted from the trigger, adopting a nominal integration time \( \Delta t = 0.5t \) throughout. As can be seen in Figure 1a, for a burst at low redshift, \( z = 0.32 \), the GeV emission from all three models can be detected by GLAST up to a time \( t \sim 1.5 \times 10^5 \) s (the thick solid line indicates the LAT sensitivity). Note that the GeV emission from the standard model is higher than that from the other two models. This is because all the models end up with the same energy and the same parameters at late times, which means the injection model starts with lower energy and the evolving-parameter model begins with a lower \( \epsilon_e \). Figure 1b shows the synchrotron and IC spectra of the standard model (A) at times \( t = 10^2, 10^3, 10^4, 10^5, \) and \( 10^6 \) s. Hereafter, unless otherwise stated, we always calculate the spectra at these epochs. The fluxes around 1 TeV (10\(^{12}\) eV) show the effects of including photon-photon absorption within the sources. The upper curves are the flux without \( \gamma-\gamma \) absorption, and the lower curves are the flux after internal absorption. For this we have used the optical depth.

![Figure 3](image.png)
to internal $\gamma\gamma$ interactions from equation (20) of Zhang & Mészáros (2001). For the relatively low compactness parameters of the external afterglow shock discussed here, the $\gamma\gamma$ cutoff becomes important above energies of $\sim 1$ TeV, which are of more interest for ground-based air Cerenkov telescope observations than for space detectors. Figures 1c and 1d show the redshift dependence of the GeV emission for all three models at $t \sim 1.1 \times 10^3$ s and at $t \sim 2 \times 10^4$ s. At $t \sim 1.1 \times 10^3$ s, the limiting redshift is $z \sim 0.4$ for the standard model and $z \sim 0.22$ for the other two models. At $t \sim 2 \times 10^4$, the limiting redshift is around $z \sim 0.45$ for all three models.

Note that while the usual fluence is defined as flux integrated over the observation time since the trigger, which always increases with time, the partial fluences shown in Figure 1a first increase and eventually decrease. This is because the afterglow flux decreases with time $t$, and for the partial fluences the integration time starts at $0.5t$ and ends at $t$. This is done to check the limiting redshift to which afterglows can be detected for typical observations at different epochs with some uniform criterion for the integration time. The snapshot at $2 \times 10^4$ s lies where the partial fluence is roughly flat in time, during which period the limiting redshift reaches its maximum (although the partial fluence within the flat phase varies by a factor of $\leq 2$, the limiting redshift changes only slightly). Other snapshot epochs were chosen around 1 decade earlier or later than the typical maximum-redshift epoch.

In Figure 2, we consider an alternate set of parameters. The motivation for this is that the parameters of the standard model shown in Figure 1, $E_{52,iso} = 1$ and $e_e = 0.5$, differ somewhat from the “statistical average” values quoted for low-redshift GRBs, $E_{52,iso} = 0.1$, $e_e = 0.1$ (e.g., Panaitescu & Kumar 2001). In order to check the sensitivity of the detectability of GRBs to variations in these parameters, we performed the same calculation using the values $p = 2.2$, $e_e = 0.2$, $e_B = 0.01$, $E_{52,iso} = 10$, $n = 1$ cm$^{-3}$, and $\theta = 0.14$ rad, the results being shown in Figure 2. For these “average” parameters, the limiting redshift is $z \sim 0.8$ for all three GRB models at $t \sim 2.0 \times 10^4$ s.

In Figure 3, we show the corresponding results for AGILE. This is a smaller scale mission than GLAST, and it is interesting to compare its detection limits with those of GLAST. AGILE has an energy range (30 MeV to 50 GeV) that is narrower than the LAT energy band (20 MeV to 300 GeV), as well as a lower effective area. Thus, the observed fluxes and partial fluences are expected to be lower. This can be seen in Figure 3a. The dashed lines are for AGILE, and the solid lines are for GLAST, showing that it is hard for AGILE to detect a burst with the typical parameters at $z = 0.32$, while GLAST could detect one for around 2 days. Figures 3b, 3c, and 3d show the detectability with AGILE and with GLAST at different epochs. At $t = 1.1 \times 10^3$ s, AGILE can detect bursts up to $z \sim 0.25$ and GLAST can detect bursts to $z \sim 0.8$. At $t = 2.0 \times 10^3$ s, the limiting redshifts are 0.15 for AGILE and 0.8 for GLAST (same as Fig. 2). At $t = 1.4 \times 10^3$ s,
the limiting redshift for AGILE is apparently well below $z = 0.1$, while the limiting redshift for GLAST still reaches up to 0.5. We see that the limiting redshift for AGILE drops relatively quickly with increasing observation time; the short-time sensitivity for AGILE lasts around $10^3$ s, and after that the sensitivity drops quickly. For GLAST, the short-time sensitivity lasts longer, $\sim 10^4$ s, and since the GeV afterglow flux does not change much for up to 1 day after the trigger, we do not expect the drop in sensitivity to have much of an effect on the limiting redshift for GLAST.

In Figure 4, we probe the sensitivity of the detectability to the total kinetic energy of the burst, taking as an example the results for a value $E_{52,iso} = 100$. This is in the range of values derived for objects such as GRB 990123 and GRB 050904, which might be called “hyperenergetic GRBs.” For the case of the standard model (A), with this energy we see that the limiting redshift for a GLAST detection has increased from $z \approx 0.8$ to $z \approx 2.0$ (Fig. 4, top), assuming that the other parameters remain the same as in Figure 2. Thus, hyperenergetic bursts such as GRB 990123, at an observed redshift of $z = 1.6$, should be detectable by GLAST in the GeV band if they have the above conventional parameters. The other hyperenergetic object, GRB 050904, has a kinetic energy similar to GRB 990123, but it was at the much higher redshift $z = 6.29$, which appears to be out of range for GLAST. GRB 050904 has the most complete set of observational data so far, covering the Swift Burst Alert Telescope band, through X-rays, to the optical/near-IR and the radio band. Thus, much effort has been invested in obtaining the best-fitting parameters for this burst (Frail et al. 2006; Gou et al. 2007). Taking the best-fitting parameters from model B of Gou et al. (2007), our results here indicate that such GRB 050904–like bursts could be detected by GLAST up to $z \leq 1.0$. There are two reasons for the relatively modest limiting redshift for GLAST in this case: (1) the electron equipartition parameter derived is small, $\epsilon_e = 0.026$, which means that only a fraction of the kinetic energy is radiated, and (2) the Compton parameter in the fast-cooling case is relatively small, $Y \approx 1.7$, which means that the energy lost through IC scattering is comparable to the energy lost by means of synchrotron radiation.

In Figure 5, we illustrate the sensitivity of GeV detectability to the value of the Compton $Y$-parameter, showing the fluxes for two values, $Y = 2.7$ (thin solid lines) and $Y = 6.6$ (dash-dotted lines) in the fast-cooling case. The parameters are same as those of the standard case (A) in Figure 2 except for the electron equipartition parameter, which is $\epsilon_e = 0.1$ for the $Y = 2.7$ case and $\epsilon_e = 0.5$ for the $Y = 6.6$ case. One would expect a higher flux over the GLAST energy band for $Y = 6.6$, because a larger Compton parameter means that more energy goes into the GeV band through the IC process, which can be seen from the spectra in the bottom panels. The limiting redshifts for an observation time of $t = 2 \times 10^4$ s are $z = 0.55$ and $z = 1.2$, respectively, for $Y = 2.7$ and $Y = 6.6$.

4. DISCUSSION

We have calculated time-dependent GeV synchrotron and inverse Compton spectra for three generic types of GRB afterglows that, at lower photon energies, have been used to interpret observations from the Swift satellite and other ground-based facilities.
These include a standard, constant-parameter afterglow model (A), a model with late energy injection (B), and a model with varying parameters (C). The spectra and partial-fluence curves in the GeV range were used to estimate the detectability with GLAST and AGILE of bursts in these model categories, for various sets of parameters, at various epochs after the trigger and for various observation durations. These model spectra improve on previous calculations in several respects. In particular, in the past it has mainly been constant-parameter spectral models such as model A that were computed; here we have extended these calculations over a broader range of input parameters, based on more recent information and statistics. Models B and C have not been previously investigated in the GeV range and are motivated by recent Swift results. The GeV spectra discussed here were computed numerically, using the formalism described in Gou et al. (2007). These are compared with previous analytical synchrotron-IC spectra of type A in the Appendix.

The detectability depends most obviously on the total burst energy $E_{\nu,iso}$ and on the observation time $t$ and integration time $\Delta t$, in addition to the other parameters such as $c_\epsilon$ and $\epsilon_b$. For example, for bursts with the standard constant parameters (A) with nominal values $E_{\nu,iso} = 10^{52}$, $\epsilon_\nu = 0.5$, and $\epsilon_b = 0.01$, the limiting detection redshift with GLAST for times $t = 1.1 \times 10^5$ s and $t = 2 \times 10^4$ s and integration time $\Delta t = 0.5 t$ are roughly the same, $z \approx 0.4$ (Figs. 1b and 1c). For models with energy injection (B) or varying parameters (C), in which the final values of $E_{\nu,iso}$ or $\epsilon_\nu$ reach the same value as for model A at a later time, the detection threshold is somewhat lower for the shorter observation time, as seen in Figure 1c, since they start out weaker and build up to be comparable to model A at later times. However, for the longer of the two observation times above, the limiting redshifts are the same (Fig. 1d). For the more standard values $E_{\nu,iso} = 10^{52}$ and $\epsilon_\nu = 0.2$ (Fig. 2b), the limiting redshift for the constant-parameter model (A) at $t = 2 \times 10^4$ s goes up to $z \approx 0.8$.

For AGILE, the limiting redshifts are lower than for GLAST because of the former’s lower effective area. For a standard burst model (A) with average parameter values $E_{\nu,iso} = 10^{52}$ and $\epsilon_\nu = 0.2$, the limiting redshift is $z \approx 0.25$ at the earlier observation time $t = 1.1 \times 10^5$ s (Fig. 3b), and $z \approx 0.15$ at $t = 2 \times 10^4$ s. With AGILE, bursts can only be detected relatively early on, since the short-time sensitivity for AGILE (for which the sensitivity curve is flat in time) only lasts, for example, around $\sim 10^5$ s, versus $\sim 10^4$ s for GLAST, for a burst at $z \approx 0.3$ (Fig. 3a).

A discrimination between models A, B, and C based on GeV measurements of GRB spectral evolution in time is possible in principle, as can be seen, for example, by comparing Figure 1c and Figures 2c and 2d. However, this will require good energy and time coverage and extensive simulations over a wide range of parameter space, since changes in $E_{\nu,iso}$, $Y$ (e.g., Figs. 4 and 5), and the other afterglow parameters need to be carefully disentangled.

The limiting redshift naturally increases for larger values of $E_{\nu,iso}$. For example, for GLAST with an observation time $t = 2 \times 10^4$ s and a standard model (A) with $E_{\nu,iso} = 10^{52}$ and $\epsilon_\nu = 0.2$, it is $z \approx 2$, while for a for a burst with the parameters of GRB 050904 (high $E_{\nu,iso}$ but low $\epsilon_\nu$), it is $z \approx 1$. The limiting redshift also increases with the Compton $Y$-parameter, as illustrated in Figure 5, which reflects the fact that $Y$ provides a measure of how much energy gets scattered into the GeV range.

Besides the photon-photon absorption inside the source considered in our calculation, another interesting absorption process is the photon-photon absorption by the external cosmic infrared background radiation (external absorption), which produces electron-positron pairs; the resulting pairs can IC-scatter the cosmic microwave background photons, yielding a delayed MeV–GeV emission (Dai & Lu 2002). It can be shown that the external absorption does not affect the limiting redshift much. Salamon & Stecker (1998) show that at $z = 1$, the absorption optical depth is $\tau \approx 1$ for photons with an energy of 50 GeV, and $\tau \approx 10$ for photons of 300 GeV. If we define the cutoff energy as the photon energy corresponding to an optical depth $\tau = 1$, the cutoff energy should shift to higher energies as one considers lower redshifts, based on the numerical results of Salamon & Stecker. Assuming that (1) photons above 50 GeV are totally absorbed and there is no absorption below 50 GeV, (2) the cutoff energy is roughly the same within the redshift range considered, and (3) the flux contribution from the delayed emission is ignored, we can conclude that in this case, the flux observed by GLAST will be comparable to that observed by AGILE, because the effective observing band will have become similar for both instruments (as a result of external absorption’s effectively cutting off the GLAST higher energy contribution). The limiting redshift for AGILE, as shown in Figure 3, will be approximately the same for the case with external absorption as it is without, because absorption is important only above the AGILE band.

The detectability estimates discussed here illustrate the sensitivity to different types of assumptions in current synchrotron–inverse Compton models, when one takes into account newer information gleaned from Swift. Calculations using simplified generic models show that some tens of Swift-detected GRBs per year will fall in the LAT field of view (Omodei et al. 2006) during their prompt emission phase. Considering the Swift-detected burst redshift distribution to imply a fraction of around 20% below $z = 1$ (Jakobsson et al. 2006; Le & Dermer 2007), we may expect about five Swift-burst prompt detections per year by GLAST. However, since the GeV afterglows can last up to a day (e.g., Figs. 1a and 2a), GLAST may actually be able to observe more than this number of bursts in the afterglow, as opposed to the prompt phase. Detections with GLAST should test many of the assumptions that go into these models and will provide important new information on the energetics, dynamics, and parameters of GRB afterglows.

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APPENDIX

We discuss here two analytical approximations to the synchrotron-IC spectrum and compare them with the numerically calculated values. The two key elements in the simple analytical approximations to synchrotron-IC spectra in the literature are (1) an IC-to-synchrotron peak flux ratio,

$$F \equiv f_{IC}^{max}/f_{syn}^{max}$$

(A1)
expressed, for example, in ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ and evaluated at the frequencies where the synchrotron and the IC flux attain their peak values, and (2) a “Compton parameter” $Y$, usually taken to be

$$Y = (-1 + \sqrt{4\epsilon_c/\epsilon_B + 1}/2).$$  \hfill (A2)

In the GRB literature, the flux ratio (eq. [A1]) of the analytical approximations has appeared in several forms, two of which are the most relevant for us here. One of these is

$$F_1 \equiv f_{\text{IC}}^{\text{peak}} / f_{\text{syn}}^{\text{peak}} = (14/45)\sigma_t R_n \simeq \tau$$  \hfill (A3)

(see eq. [A9] of Sari & Esin 2001), where $\sigma_t$ is the Thomson scattering cross section, $R$ is the shock radius, $n$ is the external circumburst density in units of cm$^{-3}$, and $\tau = \sigma_t R / 3$ is the Thomson optical depth of the radiation region. Another form that has been used is

$$F_2 \equiv f_{\text{IC}}^{\text{peak}} / f_{\text{syn}}^{\text{peak}} = [4(p-1)/(p-2)]^\tau$$  \hfill (A4)

(Kobayashi et al. 2007). It is apparent that $F_1$ is smaller than $F_2$ by a factor of $[4(p-1)/(p-2)]$, which can produce substantial differences in analytical estimates of the IC spectral flux at its peak. It is therefore worthwhile to clarify the reason for the discrepancy.

The $F_1$ form of the peak flux ratio is derived from an integral over the electron energy distribution and a power-law seed synchrotron spectrum (see eq. [7.28] of Rybicki & Lightman 1979; see also eq. [A1] of Sari & Esin 2001). The $F_2$ form, on the other hand, is obtained by solving for $f_{\text{IC}}^{\text{peak}} / f_{\text{syn}}^{\text{peak}}$ from an equation that relates the Compton $Y$-parameter to the ratio of the luminosities produced by the first-order IC and the synchrotron mechanisms:

$$Y = L_{\text{IC,1st}} / L_{\text{syn}} \sim \nu_{\text{peak}}^{\text{IC}} f_{\nu} / \nu_{\text{peak}} f_{\nu} = 2\kappa r_a^2 m_e c$$  \hfill (A5)

(Kobayashi et al. 2007), where $\nu_{\text{peak}}^{\text{IC}}$ and $\nu_{\text{peak}}$ are the peak frequency of the IC and synchrotron spectra, respectively, and $f_{\nu} / \nu_{\text{peak}}$ are the peak fluxes corresponding to the IC and synchrotron peak frequencies. The corresponding analytical approximation to the IC spectrum is simpler than in the previous $F_1$ case, in that it is a broken power law (without logarithmic corrections). In the low-frequency part of the IC spectrum, the broken power law is a good approximation to a numerically calculated IC spectrum. However, in the high-frequency part, the broken power law analytical approximation underestimates the numerical IC spectrum, which is larger (and has a flatter spectral index) than the broken power law prediction (this underestimate is avoided in the $F_1$ case by including the logarithmic correction). In the $F_2$ pure broken power law case, therefore, in order to keep the frequency-integrated total luminosity radiated by the IC mechanism equal to the numerically computed total IC luminosity, and to preserve the desirable simple broken power law shape, an artificially boosted peak flux ratio is adopted, which leads to the same IC-to-synchrotron luminosity ratio. Thus, while the total energetics are the same for both analytical approximations, the IC flux expected over the GLAST (and AGILE) energy range differs. Whereas $F_2$ is simpler for quick estimates, since it involves pure power laws and correctly describes the global energetics, $F_1$ with the logarithmic corrections to the power laws is preferable for more accurate GeV spectral flux estimates.

The optical depth here differs from the usual definition by a factor of $\frac{1}{3}$, but for consistency with the literature (Panaitescu & Kumar 2000; Kobayashi et al. 2007), we keep the factor of $\frac{1}{3}$ here.

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