Prospects for Detecting Gamma-Ray Bursts at Very High Energies with the Cherenkov Telescope Array

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ABSTRACT
We discuss the prospects for the detection of gamma-ray bursts (GRBs) by the Cherenkov Telescope Array (CTA), the next generation, ground-based facility of imaging atmospheric Cherenkov telescopes (IACTs) operating above a few tens of GeV. By virtue of its fast slewing capabilities, the lower energy threshold compared to current IACTs, and the much larger effective area compared to satellite instruments, CTA can measure the spectra and variability of GRBs with excellent photon statistics at multi-GeV energies, which would revolutionize our understanding of the physics of GRBs, test their validity as the origin of ultra-high-energy cosmic rays, and provide powerful probes of the extragalactic background light as well as Lorentz-invariance violation. Employing a model of the GRB population whose properties are broadly consistent with observations by the Gamma-ray Burst Monitor (GBM) and Large Area Telescope (LAT) onboard Fermi, we simulate follow-up observations of GRBs with the Large Size Telescopes (LSTs), the component of CTA with the fastest slew speed and the best sensitivity at energies below a few hundred GeV. For our fiducial assumptions, we foresee that the LSTs can detect \( \sim 0.1 \) GRBs per year during the prompt phase and \( \sim 0.5 \) per year in the afterglow phase, considering only one array site and both GBM and the Space-based multi-band astronomical Variable Object Monitor (SVOM) as the alert instruments. The detection rates can be enhanced by a factor of about 5 and 6 for the prompt emission and the afterglow, respectively, assuming two array sites with the same sensitivity and that the GBM localization error can be reduced to less than 1\( ^\circ \). The expected distribution of redshift and photon counts are presented, showing that despite the modest event rate, hundreds or more multi-GeV photons can be anticipated from a single burst once they are detected. We also study how the detection rate depends on the intrinsic GRB properties and the delay time between the burst trigger and the follow-up observation.

Key words: radiation mechanisms: non-thermal – gamma-ray burst: general

1 INTRODUCTION
Gamma-ray bursts (GRBs) are the most violent explosive phenomena in the Universe. The prompt emission of GRBs typically has luminosity of \( L_\gamma \sim 10^{51} \text{–} 10^{52} \text{ erg s}^{-1} \) at \( \sim 0.1 \text{–} 1 \text{ MeV} \), and the following long-lasting afterglow emission is observed in the radio to X-ray bands (see reviews, Mészáros 2006; Zhang 2007). High-energy gamma-ray emission above \( \sim 0.1 \) GeV was first seen by the Energetic Gamma-Ray Experiment Telescope (EGRET) detector on-board the Compton Gamma Ray Observatory (e.g., Hurley et al. 1994; Gonzalez et al. 2003). The Large Area Telescope (LAT) on-board the Fermi satellite has recently detected high-energy gamma rays from a much larger sample of GRBs (Abdo et al. 2009a,b,c, 2010, 2011; Ackermann et al. 2010, 2011). The LAT GRBs exhibit the
following features (see recent reviews, Granot et al. 2010; Bhat & Guiriec 2011; Pe’er 2011; Inoue et al. 2012): (a) Most of the LAT GRBs do not show significant suppression at the high-energy end of their spectra, though observed LAT limits on the GeV fluence for the GRBs detected by the Gamma-ray Burst Monitor (GBM) onboard the Fermi satellite may suggest a steeping or cutoff in the high-energy spectrum [Beniamini et al. 2011]; (b) Some of the LAT GRBs have an anomalous extra component in the > 0.1 GeV range [Abdo et al. 2009c; Ackermann et al. 2011]; while others show a high-energy spectrum consistent with the Band function [Band et al. 1993]; (c) in many cases, the emission onset in the > 0.1 GeV energy range is delayed relative to that in the < 1 MeV energy range. (d) The LAT GRBs often show the long-lived high-energy emission lasting longer than the duration of the sub-MeV component; (e) Not only long GRBs but also short GRBs seem to have the above features [Ackermann et al. 2010]. Understanding these features is likely to give us important clues to GRB mechanisms and related astrophysics.

The Cherenkov Telescope Array (CTA), under plan as the next generation international gamma-ray observatory (CTA Consortium 2010, 2011), will provide a great step forward in studying these issues. CTA will be constructed at two sites, one each in the northern and southern hemispheres, and comprises three types of telescopes: the Large Size Telescopes (LSTs) with 23 m diameter and 4.6° field of view (FOV); the Medium Size Telescopes (MSTs) of 12 m and 8° FOV; and the Small Size Telescopes (SSTs) of 7 m and 10° FOV. With CTA, the sensitivity will improve by a factor of 5–10 in the 0.1–10 TeV range compared to existing 100 TeV, and the angular and energy resolution will be appreciably increased. In the following, we summarize open issues that can be unraveled by CTA. We refer the reader to [Inoue et al. 2012] for an extensive overview on the science prospects for GRB observations with CTA.

(i) The bulk Lorentz factor \( \Gamma \) is one of the key quantities in understanding the properties of relativistic jets making GRBs. It is thought to be limited to order of \( \sim 1000 \) in the classical fireball model with baryons, whereas higher Lorentz factors may be achieved by Poynting-dominated jets (e.g., Spruit et al. 2001) or radiation-dominated jets with dissipation via e.g., jet-confinement [Ioka et al. 2011] or baryon-entrainment [Ioka 2010]. The bulk Lorentz factor can be constrained from observations of the high-energy end of the spectra [Lithwick & Sari 2001], and absence of high-energy cutoffs for the LAT GRBs have indeed given us lower limits on \( \Gamma \) (e.g., Abdo et al. 2009a,b). In the case of GRB 090926A [Ackermann et al. 2011], a sharp softening of the spectrum is observed at \( \sim 1.4 \) GeV, and interpreting this as the pair-creation cutoff leads to \( \Gamma \approx 720 \). However, such estimates can be affected by the finite extent of the emission region [Baring 2006], time-dependence of the photon field [Granot et al. 2008; Asano & Mészáros 2011], and multiple emission regions [Li 2010; Aoi et al. 2011; Hascott et al. 2011], so that the resulting high-energy spectra can be more complicated. For more detailed studies, observations with much better statistics are required. CTA will be ideal for these purposes.

(ii) The mechanism of the prompt emission is one of the most critical issues in the theory of GRBs. In the classical scenario, \( \sim \) MeV emission is explained by the optically-thin synchrotron radiation from electrons accelerated at internal shocks [Rees & Mészáros 1994]. However, this classical scenario has several problems in explaining observations (see reviews, Mészáros 2006; Zhang 2007), and many alternative scenarios such as the photospheric dissipation scenario [e.g., Thompson 1994; Mészáros & Rees 2000; Rees & Mészáros 2005; Ioka et al. 2007; Beloborodov 2010; Murase et al. 2012] and magnetic dissipation scenarios (e.g., Luidik et al. 2000; Zhang & Yan 2011; McKinney & Uzdensky 2011) have been suggested. For the mechanisms of the > 0.1 GeV emission, both leptonic and hadronic emission have been proposed. Synchrotron emission [Wang et al. 2009; Ioka 2010; Daigle et al. 2010], synchrotron self-Compton (SSC) emission [Corsi et al. 2010a,b], external inverse-Compton (EIC) emission [Toma et al. 2009, 2011b], and proton synchrotron or proton-induced cascade emissions [Asano et al. 2009b, 2010; Razzaque et al. 2010; Murase et al. 2012] are currently viable explanations. However, once the prompt emission is detected by CTA, it may be possible to discriminate among the emission mechanisms by analyzing the very-high-energy (VHE) spectrum and variability with high photon statistics.

(iii) It is believed that the long-lived high-energy component is related to the afterglow emission. In the simplest scenario, the high-energy emission is explained by synchrotron emission from the non-radiative external forward shock with extreme parameters [Kumar & Barniol Duran 2011] or radiative external forward shock [Ghisellini et al. 2010]. The Klein-Nishina effect may play a role in the initial rapid decay [Wang et al. 2010], but the more natural explanation is the gradual turn-off of the prompt emission [Lin & Wang 2011; He et al. 2011; Maxham et al. 2011]. One of the important tests for synchrotron external shock scenarios is to see the maximum synchrotron cutoff that decreases as the Lorentz factor declines [Piran & Nakar 2010], and CTA may eventually see the SSC emission component.

Observations by CTA can also provide a clue to the origin of X-ray shallow-decay emission. The shallow-decay behavior is observed in most X-ray afterglows of \textit{Swift} GRBs [Nousek et al. 2008; O’Brien et al. 2008; Zhang et al. 2009], though it was not predicted by the standard afterglow model (Mészáros & Rees 1997; Sari et al. 1998). Its origin has been debated for many years, and possible models include energy injection (e.g., Dai & Liu 1998; Rees & Mészáros 1998; Zhang et al. 2006), the long-lasting internal activity (Ghisellini et al. 2007; Kumar et al. 2008; Murase et al. 2011), the long-lasting reverse shock [Genet et al. 2007; Uhm & Beloborodov 2007], time-dependent microphysics [Ioka et al. 2006], effect of cosmic ray escape [Dermer 2007], bulk Compton emission [Panaitecu 2008a], prior emission [Yamaoka 2009], and multi-component jets (e.g., Eichler & Granot 2000; Toma et al. 2006). These models should predict different high-energy emissions [Fan et al. 2008; Panaitecu 2008a; Murase et al. 2010, 2011], so that the simultaneous observations by \textit{Swift} and the Space-based multi-band astronomical Variable Object Monitor (SVOM) [Paul et al. 2011] as well as CTA would be useful for discriminating among the models. On the other hand, high-energy emission has been ob-
served concurrently with X-ray flares, which are often seen in the early afterglow phase (Abdo et al. 2011). Although they are considered to originate from some internal dissipation processes rather than external shocks (Ioka et al. 2003), their mechanism and the origin of the high-energy emission is still unclear. CTA may provide a breakthrough for revealing these problems.

(iv) VHE signals from GRBs can be useful for other purposes. GRBs may be the main sources of the observed ultrahigh-energy cosmic rays (UHECRs) (Waxman 1995a; Vietri 1995). If this hypothesis is true, VHE gamma rays provide one of the crucial probes, and detections of characteristic signals, including hadronic cascade radiation (Böttcher & Dermer 1995; Pe’er & Waxman 2003; Dermer & Atöyan 2006; Asano et al. 2009a; Murase et al. 2012), ion synchrotron radiation (Böttcher & Dermer 1995; Totani 1998a,b), synchrotron pair-echo emission induced by ultra-high-energy photons (Murai et al. 2012), and emission via nuclear photodisintegration and Bethe-Heitler pair production (Murai & Beacom 2010), are relevant to test this GRB-UHECR hypothesis. Also, VHE gamma rays from GRBs are useful as a probe of the Universe. Since they are attenuated by the extragalactic background light (EBL), one can constrain the EBL by measuring the attenuation as in the case of blazars (e.g., Aharonian et al. 2006; Albert et al. 2007). VHE gamma rays also lead to secondary emission as a result of interactions with the EBL, and detections or non-detections of this pair-echo emission enable us to probe the uncertain intergalactic magnetic fields in voids as well as the EBL (e.g., Razzano et al. 2004; Takahashi et al. 2008; Murase et al. 2009a). GRBs may occur even at the very distant universe, $z > 5$ (e.g., Kawai et al. 2006; Salvaterra et al. 2008; Tanvir et al. 2009), and VHE gamma rays might be generated by GRBs originating from population III stars (Toma et al. 2011). If we detect the attenuated VHE gamma rays from such distant GRBs, it would be possible to constrain the EBL in the high-redshift universe (Gilmore et al. 2003; Inoue et al. 2010) and/or cosmic magnetic fields at high redshifts (Takahashi et al. 2011). In addition, one can obtain insight into fundamental physics. For example, using the temporal (and spectral) information, one can test the Lorentz-invariance violation predicted in some quantum gravity theories (e.g., Amelino-Camelia et al. 1999; Abdo et al. 2009a; Shao & Ma 2010).

As described above, CTA should be a powerful tool to understand GRB physics and test various ideas and hypotheses related to GRBs. VHE gamma-ray astronomy has now been firmly established by state-of-the-art IACTs such as H.E.S.S., MAGIC, and VERITAS. A firm detection of GRBs has not been reported so far (Albert et al. 2007; Aharonian et al. 2009; Aleksić et al. 2010), but CTA may eventually achieve the goal with much lower energy threshold and much better sensitivity, which will also allow us to obtain time-resolved spectra of much better quality than ever before in the energy range greater than a few tens of GeV. In this work, we report the prospects for detecting long GRBs (durations longer than 2 sec) with CTA, and how the results depend on some of the array performance and GRB properties. The situation considered here is that GRBs are detected by some satellites and followed up by the LSTs, which will play a principal role in GRB observations. In our simulation, we mainly assume Fermi/GBM as the burst trigger, which has already provided data with high statistics and may be active in the CTA era. We also make a rough estimate for the alerts from the SVOM satellite, which is planned to be launched before CTA operation. Some complementary aspects of this work are also presented in Inoue et al. (2012).

The organization of the paper is as follows. In section 2, we describe the intrinsic GRB properties of both prompt and afterglow emissions in our simulations. In section 3, we model the performance of the LSTs and the follow-up observation of GRBs. Performing Monte Carlo simulation, we estimate the detection rate of GRBs with the LSTs in section 4. Finally, section 5 is devoted to summary and discussion. We use cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

# 2 INTRINSIC GRB PROPERTIES

In this section, we describe our method of generating the intrinsic GRB samples in our Monte Carlo simulations and the assumed EBL model. It provides each sample with the prompt and afterglow properties using a luminosity function and well-known spectral correlations. We consider the GRB samples only with the duration $> 2$ sec and redshift $< 5$. It is also shown that our sample is consistent with some observational results of GBM and LAT onboard Fermi.

## 2.1 Prompt emission

We assume the luminosity function of GRBs, defined as the rate of GRBs per unit comoving volume at a redshift $z$, is still unclear. CTA may provide a breakthrough for revealing the characteristic signals, including hadronic cascade radiation. In our fiducial case, $L_p \approx 10^{54}$ erg s$^{-1}$ cm$^{-2}$ in the 8–10 keV band, satisfied by $L_\gamma \approx 10^{44}$ erg s$^{-1}$ s$^{-1}$ assuming its trigger condition as the peak photon flux of $1 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ afterglow emission. GRBs may be the main sources of the observed one, where $T_{\text{delay}}$ is the time needed to accumulate from 5% to 95% of observed photon counts. The reason is that the delay time $T_{\text{delay}}$, which is
the start time of a follow-up observation as measured from the burst trigger time, is required to be shorter than the burst duration for the detection of the prompt emission. In order to determine \( T_{90} \) of our simulated GRB samples, at first we assume that the duration of the prompt emission in the energy range where the LSTs are most sensitive (from \( \sim 10 \) GeV to \( \sim 100 \) GeV) is equal to \( T_{90} \) in the GBM band, and that the prompt phase provides constant gamma-ray luminosity \( L_{\text{ave}} \), evaluated by averaging the highly variable light curve. To determine the value \( L_{\text{ave}} \) from the peak luminosity \( L_p \), we take the average of \( (E_{\text{iso}}/T_{90})/L_p \) in the observed events (Ghirlanda et al. 2004, 2009, 2010), where \( T_{90} = T_{90}/(1 + z) \) and \( E_{\text{iso}} \) is the isotropic-equivalent gamma-ray energy. The data of \( T_{90} \) are taken from the GCN circulars. Then, we found \( (E_{\text{iso}}/T_{90})/L_p = 0.3 \pm 0.2 \). Despite the large scatter, we set

\[
L_{\text{ave}} = 0.3 L_p,
\]

for all the simulated bursts. Next, we examine a correlation between log \( L_p \) and log \( E_{\text{iso}} \) (Ghirlanda et al. 2012) employing a chi-square fit with the effective variance weighting, and obtain

\[
\log E_{\text{iso},52} = 1.1 \log L_{p,52} + 0.56,
\]

with a standard deviation of 0.49 dex. Using this relation and taking the standard deviation into account, \( E_{\text{iso}} \) is determined by \( L_p \) in our simulation. Then, we determine the duration as

\[
T_{90}' = E_{\text{iso}}/L_{\text{ave}},
\]

and \( T_{90} = (1 + z)T_{90}' \).

As the intrinsic spectral shape of the GRB prompt emission, we assume the Band function, which is given by Band et al. (1993) as

\[
N_E \propto \begin{cases} E^\alpha \exp(-E/E_0) & E \leq (\alpha - \beta)E_0 \\ E^{\beta} & E > (\alpha - \beta)E_0 \end{cases},
\]

where \( \alpha \) and \( \beta \) are the high- and low-energy photon indices, respectively. If \( \beta < -2 \) and \( \alpha > -2 \), then the \( \nu F_\nu \) spectrum has a peak at \( E_p = (2 + \alpha)E_0 \). For given \( L_p \), we determine \( E_p \) according to the \( E_p-L_p \) relation examined by Ghirlanda et al. (2009) (the so called Yonetoku relation: Yonetoku et al. 2004) taking the standard deviation into account. The average luminosity \( L_{\text{ave}} \) determines the normalization of the Band function. The photon indices \( \alpha \) and \( \beta \) are determined according to the distribution that was actually observed for bright BATSE bursts (Kaneko et al. 2006). In our fiducial case, only the bursts with \( \beta < -2 \) are treated.

In summary, the luminosity function provides \( L_p \) and \( z \) for each generated burst, which are subsequently related to \( E_{\text{iso}}, L_{\text{ave}}, T_{90} \) and \( E_p \). Photon indices \( \alpha \) and \( \beta \) are determined independently.

For a check of the validity of our method that generates GRB samples, we simulate the bursts triggering GBM and compare their \( T_{90} \) and fluence distributions with observations. The observed data (from GRB 080714 to 101130) were taken from the GCN circulars. In the top panel of Figure 1, the scatter plot of the fluence and \( T_{90} \) for both the simulated and the observed GBM samples are shown. In the bottom panel of the same figure, we show the simulated fluence distribution for GBM bursts in the 8–10³ keV band superposed on the observed one. Both panels of Figure 1 show that the actually observed properties of fluence and \( T_{90} \) are well reproduced by our model. We find that 20 % of the GRBs in our simulation have \( T_{90} \) larger than 100 sec, the typical value of \( T_{\text{delay}} \) assumed in our fiducial case as described later. This is only slightly larger than that for actually detected events (16 %). Our modelled duration distribution can be considered to be in sufficiently good agreement with the observed one for our purposes of estimating the detection rates.

Furthermore, we verify that our method roughly agrees with the Fermi/LAT detection rate, which is estimated as follows. First, we estimate the all-sky event rate to be \( \sim 1000 \text{ yr}^{-1} \) for the bursts satisfying \( T_{90} > 2 \) sec and \( z < 5 \) by deconvolving the observed GRB trigger rate of 250 yr⁻¹ with the FOV of GBM (9.5 sr) and the trigger efficiency of GBM obtained with our simulation. Next, we calculate the detection efficiency of LAT for the bursts satisfying both \( T_{90} > 2 \) sec and \( z < 5 \) using our intrinsic GRB model, where a burst is judged to be detectable with LAT when the number of detected photons > 100 MeV by LAT is larger than 10. Here we take the LAT effective area from Atwood et al. (2009) and consider the signal-dominated regime where the background can be neglected, and take into account its dependence on incidence angle \( \theta \) simply by a factor of \( \cos \theta \).

The incidence angle is isotropically distributed in the LAT FOV. Then, combining the above derived values with the

\footnote{http://gammaray.msfc.nasa.gov/gbm/instrument/description/character.html.}
LAT detection rate to be 12 yr⁻¹ (Atwood et al. 2009), we estimate the uncertainty in the case of a tent with the observed one, about 7–8 yr⁻¹ (Granot et al. 2004) at \( z = 1 \). Strictly speaking, our simulated LAT detection rate is slightly overestimated. Better agreement may possibly be achieved by accounting for spectral softening below the LAT band suggested for subset of events (Beniamini et al. 2011), a more sophisticated model of LAT detection conditions, etc. We leave this issue as future work (though a brief discussion will be given in Section 5).

For the estimate of the detection rate with CTA/LSTs, we also simulate the case in which the prompt emission has an extra hard component in addition to the Band spectral component. Such an extra component has been confirmed by Fermi/LAT in some bursts (Abdo et al. 2009a, Ackermann et al. 2010). However, at present, the properties of the extra component, such as its spectral slope, amount of released energy, and the fraction of the event with the extra component, are highly uncertain. Therefore we introduce another parameter, \( R_{\text{extra}} = L_{\text{extra}}/L_{\text{iso}} \), where \( L_{\text{extra}} \) is the luminosity of the extra component in the 0.1–100 GeV band. Roughly speaking, \( R_{\text{extra}} \) is the ratio of the LAT band luminosity to that of GBM. For LAT bursts, \( R_{\text{extra}} \) is about a few 10% (Ghisellini et al. 2010), and from the EGRET and LAT observations, the photon index in the GeV region is about –2 on average (Dingus 1995, Ghisellini et al. 2011). Below, for simplicity, we assume that all simulated bursts have the same \( R_{\text{extra}} = 0.1 \) and a photon index of –2. Figure 2 illustrates examples of the \( \nu F_{\nu} \) spectrum of the prompt emission for the case of \( R_{\text{extra}} = 0 \) and 0.1. In both the cases, \( \alpha = -1.0, \beta = -2.5, E_p = 250 \) keV, and \( z = 1 \) are adopted. Cutoffs near 100 GeV are caused by the EBL attenuation modeled by Razzaque et al. (2009). We need to take into account the attenuation of gamma-ray photons by the EBL. In our fiducial case, we adopt the EBL model of Razzaque et al. (2009). This model is applicable for \( z < 5 \), so that only bursts with \( z < 5 \) are considered in our simulation. As we see later in Figure 3, higher-redshift (\( z > 5 \)) bursts are not expected to make a significant contribution to the detection rate with CTA (see also de Souza et al. 2011). For comparison, we also make calculations with the “Best Fit 06” EBL model of Kneiske et al. (2004) at \( z < 5 \). In this model, the gamma-ray horizon, the location where the \( \gamma \gamma \) optical depth \( \tau_{\gamma\gamma} (E, z) = 1 \) lies at lower-redshift by a factor of \( \sim 1–2 \) at \( E < 100 \) GeV compared to our fiducial EBL model. However, we found that the resulting differences in the detection rate and the redshift distribution for these two models is not large.

2.3 EBL attenuation

We need to take into account the attenuation of gamma-ray photons by the EBL. In our fiducial case, we adopt the EBL model of Razzaque et al. (2009). This model is applicable for \( z < 5 \), so that only bursts with \( z < 5 \) are considered in our simulation. As we see later in Figure 3, higher-redshift (\( z > 5 \)) bursts are not expected to make a significant contribution to the detection rate with CTA (see also de Souza et al. 2011). For comparison, we also make calculations with the “Best Fit 06” EBL model of Kneiske et al. (2004) at \( z < 5 \). In this model, the gamma-ray horizon, the location where the \( \gamma \gamma \) optical depth \( \tau_{\gamma\gamma} (E, z) = 1 \) lies at lower-redshift by a factor of \( \sim 1–2 \) at \( E < 100 \) GeV compared to our fiducial EBL model. However, we found that the resulting differences in the detection rate and the redshift distribution for these two models is not large.

3 MODELING OF GRB OBSERVATIONS WITH CTA/LSTS

In this section, we model the CTA observation of GRBs to investigate the GRB detection rate and the expected GRB properties. The arrays for CTA will be constructed at two sites, each in the northern and southern hemispheres, and designed to have three types of telescopes: LSTs, MSTs, and SSTs. The LSTs will be the most crucial component for detecting GRBs because they dominate sensitivity below 200–300 GeV (CTA Consortium 2011) where EBL attenuation is expected to be less severe, and have the capability of fast slewing (180° in 20 sec). In this paper, we consider only one array site and the sensitivity of LSTs alone unless it is explicitly stated otherwise.

We consider the situation where GRBs are detected by GBM and then are followed up by the LSTs, pointing to the centroid of the GBM error circle. Bursts that occur by chance in the LST FOV are not considered because their detection rate is expected to be very low.

2.2 Afterglow emission

High-energy afterglow emission in the CTA band is also highly uncertain. Then, following Ghisellini et al. (2010), we assume a simple phenomenological model to describe the luminosity of the afterglow emission in the 0.1–100 GeV band as: \[ L_{\text{AG}} (T') = 10^{52} \text{erg s}^{-1} \left( \frac{E_{\text{iso}}}{10^{54} \text{erg}} \right) \left( \frac{T'}{10 \text{ s}} \right)^{p_t} , \] where \( p_t \) is the temporal decay index, and \( T' = T/(1+z) \) is the elapsed time from the burst trigger in the cosmic rest frame. We choose the normalization to reproduce the result seen in Figure 4 of Ghisellini et al. (2010). Now the isotropic-equivalent energy and the burst duration of the prompt emission, \( E_{\text{iso}} \) and \( T_{90} \), are determined as described in the previous subsection. We assume \( L_{\text{AG}} \) has nonzero value only if \( T > T_{90} \). In our fiducial case, we set the temporal and spectral energy indices \( p_t \) and \( p_E \) (i.e., \( E_{\gamma} \propto T^{p_t} \nu^{p_E} \)) to –1.5 and –1.0, respectively (Ghisellini et al. 2010).

Figure 2. Examples of the \( \nu F_{\nu} \) spectra of the prompt emission for the case of \( R_{\text{extra}} = 0 \) (dotted curve) and 0.1 (solid curve) are illustrated. For both cases, \( \alpha = -1.0, \beta = -2.5, E_p = 250 \) keV, and \( z = 1 \) are assumed. Cutoffs near 100 GeV are caused by the EBL attenuation modeled by Razzaque et al. (2009).
3.1 GBM localization

Follow-up observations are made only for sufficiently well-localized bursts. Therefore, we set a threshold value of the localization accuracy of the alerted burst for the follow-up observation. In the case of the MAGIC telescope, its FOV is 3.5°, and the threshold of the error radius to start the follow-up is 1.5° (Garczarczyk et al. 2009). In our simulation for CTA/LSTs, we set the threshold value, σth, to 3.5° (i.e., the observation is made only when the alerted error radius with 1-sigma accuracy is less than σth). The error radius of each sample is given as a function of energy fluence using the GBM burst data set, where the 1-sigma error radius of individual bursts is estimated as \((\sigma^2_{\text{stat}} + \sigma^2_{\text{sys}})^{1/2} (\equiv \sigma)\). The systematic error \(\sigma_{\text{sys}}\) of 3° is assumed for all the bursts for simplicity (Briggs et al. 2000), and the statistical error \(\sigma_{\text{stat}}\) is given by ground position data (V. Connaughton, private communication) which are reported \(\gtrsim 1\) min after the burst triggers.

From these assumptions, the fraction of the triggered bursts for which the error radius is less than \(\sigma_{\text{th}}\) is \(\approx 21\%\). Note that in most cases, only the flight position data, which are more poorly determined compared to the ground one, are available during the prompt phase. Hence, as long as the current localization capability of GBM is considered, the simulated localization efficiency (i.e., 21%) is larger than reality, which causes an overestimate of the detection rate of the prompt emission. Nevertheless, we adopt this assumption expecting the improvement of the localization speed of GBM and its accuracy by the CTA era. For the afterglow phase, the above assumption for GBM localization has little influence. Without any improvement of the GBM localization, nontrivial followup strategies that compensate for the limited FOV of the LSTs may be helpful to search for the prompt emission of GBM bursts, such as scanning the error circle over time (Finnegan & for the VERITAS Collaboration 2011), or divergent pointing of the LSTs over the error circle.

The error radius of GBM localization is always larger than the radius corresponding to the LST’s FOV of 2.3°. Hence in our simulation, we take into account the probability that the burst is in the FOV of LSTs after slewing for each burst alerted by the GBM. It is given by integrating the two-dimensional Gaussian distribution with the standard deviation of \(\sigma\) from 0 to 2.3°. In our fiducial case (i.e., \(\sigma_{\text{th}} = 3.5\)), the probability is about 20%. The dependence of the detection rate on \(\sigma_{\text{th}}\) is shown in Section 4.3.

3.2 Delay time and detection conditions of CTA

When a sufficiently well localized position of a GRB is obtained, the more rapidly CTA points toward the position, the more chances for GRB detection it has. In the case of MAGIC-I, if the distribution of the delay time between the start of observations and the GRB trigger time (\(T_{\text{delay}}\)) is fitted by a log-normal probability density function (PDF), then the PDF multiplied by \(T_{\text{delay}}\) has a peak at \(T_{\text{delay}}\) of \(\sim 160\) sec and a standard deviation \(\sigma_{\text{delay}}\) of \(\sim 0.5\) dex (Garczarczyk et al. 2003, Albert et al. 2007). Taking into account the ability of rapid slewing of the LST, we assume that \(T_{\text{delay}}\) of the LST obeys a log-normal distribution with \(\tau_{\text{delay}}\) of 100 s and \(\sigma_{\text{delay}}\) of 0.4 dex in our fiducial case. In addition we impose \(T_{\text{delay}} > 20\) sec. It may be conservative to use \(T_{\text{delay}} = 100\) sec for LSTs considering that the average slewing time of the telescope (not the delay time) of \(\sim 90\) sec for MAGIC-I (Garczarczyk et al. 2009) is more than 70 sec longer than that for LSTs, \(< 20\) sec. Simulation results for the other values of \(\tau_{\text{delay}}\) will be shown in Section 4.3.

The last step for the GRB observations is to compare the gamma-ray flux with the sensitivity of CTA. Here we define \(N_\gamma\) as the total photon counts and \(N_{\text{bg}}\) as the total background counts, where both are obtained by integration over the energy range from \(E_{\text{low}}\) to 300 GeV for a given observation time. The low-energy end of the integration \(E_{\text{low}}\) is given in the next subsection. The upper bound of the integration, 300 GeV, is sufficient for discussing the detection rate with LSTs. The exposure time is set to be \(T_{\text{exp}} = T_{\text{delay}}\) for the prompt emission and at most 4 hours for the afterglow. Following the simple estimates of telescope sensitivity (e.g., Aharonian et al. 2001, CTA Consortium 2010), we judge that a burst is detected if all of the following conditions are satisfied: (1) \(N_\gamma > N_{\text{min}}\), (2) \(N_\gamma > m\sqrt{N_{\text{bg}}}\), and (3) \(N_\gamma > eN_{\text{bg}}\), where \(N_{\text{min}} = 10\), \(m = 5\) and \(e = 0.05\). The condition (1) concerns the minimum number of photons required to create the sufficient Cherenkov radiation. The conditions (2) and (3) are about the statistical significance and the systematic error, respectively. To evaluate these conditions for each sample, we need the effective area of CTA/LSTs, background spectrum, angular resolution, and \(E_{\text{low}}\). These are given in the next subsection.

3.3 Performance of the LSTs

In this subsection, we construct a toy model for the LSTs, which reproduces the differential sensitivity of CTA that is publicly available (CTA Consortium 2010). In order to calculate the differential sensitivity of our model, we set: the effective area of LSTs after all cuts for gamma rays \(A_\gamma\), the effective area for the background
\(A_{bg}\), the background spectrum \(J_{bg}\) in units of particles \(s^{-1}cm^{-2}sr^{-1}GeV^{-1}\), and the angular resolution \(\phi\). These are given as functions of photon or particle energy. The effective area \(A_{eff}\) is approximately the same as \(A_{s}\) because the background is dominated by electrons at energies below \(\sim 100\) GeV, inducing electromagnetic showers similar to gamma rays \([\text{CTA Consortium 2016} \text{; Aharonian et al. 2001}]\). Then we assume \(A_{bg} \propto A_{s}\) and \(J_{bg} \propto E^{-3.045}\) according to the Fermi/LAT and the HESS observations of cosmic-ray electrons and positrons \([\text{Fan et al. 2011} \text{; Aharonian et al. 2008} \text{; Abdo et al. 2009}]\). In addition, assuming \(\phi \propto E^{-0.5}\) \([\text{CTA Consortium 2014}]\), we can calculate the differential count rate of the background as \(dR_{bg}/dE = \pi J_{bg} A_{bg} \phi^2 \propto E^{-4.045} A_{s}\). The normalization of \(dR_{bg}/dE\) is given below.

Once the functional form of \(A_{s}\) is given, a shape of the differential sensitivity curve (that is, its energy dependence) is determined. We found that by using the effective area of the MAGIC telescope at its trigger level as \(A_{s}\) \([\text{MAGIC Collaboration 2011}]\), we can reproduce well the shape of the official sensitivity curve of CTA at \(\lesssim 200-300\) GeV, where the LSTs dominate the sensitivity. Therefore as a functional form of \(A_{s}\) at zenith angle \(\theta_{zen} = 20^\circ\), we adopt the MAGIC effective area at the trigger level in our simulation. We normalize \(A_{s}\) introducing a factor of \(f_A\), where \(f_A = 1\) means that \(A_{s}\) corresponds to the effective area at the trigger level of MAGIC.

For any value of \(f_A\), we can fit the sensitivity curve of our model to the public one with the normalization of \(dR_{bg}/dE\). In Figure 3, the official differential sensitivity of CTA is shown as the black dotted curve for the exposure time of 0.5 h, where contributions from all types of telescopes (i.e., LSTs, MSTs, and SSTs) are included, though LSTs dominate the sensitivity for \(E \lesssim 200-300\) GeV. Because the sensitivity for this exposure time is limited by the statistical significance (see the detection condition (2) described in the last part of Section 3.2) at \(\lesssim 300\) GeV, we can determine the normalization of \(dR_{bg}/dE\) as a function of \(f_A\). In the case of \(f_A = 1\), we need \(R_{bg} \approx 0.34\) Hz for fitting, where \(R_{bg}\) is calculated by the integration of \(dR_{bg}/dE\) from 20 GeV to 20 TeV. The sensitivity curve of our model at \(\theta_{zen} = 20^\circ\) is shown as the red solid curve in Figure 3. One can see that the two curves are similar. This figure shows the photon energy up to 300 GeV since we calculate the photon counts below this energy in our simulation. Indeed, the GRB spectrum above \(\sim 100\) GeV is expected to be severely attenuated by the EBL, so that our artificial cutoff at this energy does not affect the rate estimate. Above 200–300 GeV, the MSTs and the SSTs have better sensitivity compared to the LSTs, so that the sensitivity of our model deviates from the total array sensitivity. In order to keep the two sensitivity curves consistent with each other for arbitrary value of \(f_A\), we need \(R_{bg} \approx 0.34 f_A^{2}\) Hz to normalize \(dR_{bg}/dE\) considering the detection condition (2). Although the value of \(f_A\) influences the condition (1) and (3), it varies the expected detection rate only a little (see Section 4.3). In our fiducial case, we assume \(f_A = 1\).

As \(\theta_{zen}\) increases, the shower maximum height gets higher and Cherenkov light is more absorbed, so that the area of light pool becomes large, while its density becomes low. In order to take into account the dependence of the effective area on the zenith angle, we use the following form:

\[
A_{\gamma}(E, \theta_{zen}) = \frac{1}{(\cos \theta_{zen})^2} A_{\gamma}(E', 0^\circ),
\]

where \(E' = E (\cos \theta_{zen})^\xi\), \(\xi = 1.7\) and \(\xi = 2.4\) \([\text{Aharonian et al. 1999}]\). Also for the angular resolution \(\phi\), we multiply by a factor of \((E' (\theta_{zen})/E' (20^\circ)^2)^{-1/2}\).

The differential count rate of gamma rays becomes maximum at \(\sim 60 (\cos \theta_{zen})^{-4.3}\) GeV in our model for a source with its photon index of \(-2\), neglecting the EBL attenuation. We set \(E_{low}\), which is the low-energy end of the integration for the photon counts, at an energy lower than this as

\[
E_{low} (\theta_{zen}) = 20 (\cos \theta_{zen})^{-3.3}\) GeV.
\]

As we describe in Section 4.3, the exponent of cosine, \(-3.3\), has only a small influence on the detection rate.

4 The effective area at the trigger level decreases toward the low energy more gradually than after all cuts.

### 4 GRB DETECTION RATE WITH CTA

In this section, we show the results of our Monte Carlo simulation on the GRB detection rate with the LSTs, which are obtained under the assumptions described in Section 2 and Section 3. Following is a summary of the simulation process. First, in order to generate intrinsic GRB samples, we randomly give \(L_{p}\), \(\gamma\), \(\beta\), and \(\alpha\) according to the distributions described in Section 2.1. Using several correlations with respect to the prompt emission properties, we determine \(E_{iso}\), \(L_{iso}\), \(T_{iso}\), and \(T_{90}\) from \(L_{p}\); for the first two parameters, the deviation from the best fit line of the correlation is given by a Gaussian random variable. Then, we can calculate the prompt and afterglow gamma-ray flux arriving at the Earth for each generated burst taking into account the EBL attenuation. Second, we set the trigger and the localization conditions to determine the detected and localized events. The former is given in terms of the peak photon flux, while the latter is given by the probability of sufficient localization as a function of the fluence (deduced in Section 3.1). Then it is judged whether each sample is localized sufficiently well and whether it is in the FOV of the LSTs after slewing to the best position. Finally, at the stage of follow-up observation by LSTs, \(T_{delay}\) is given by a log-normal distribution, and \(\theta_{zen}\) is isotropically distributed independently of \(T_{delay}\), where we assume a 10\% duty cycle and \(\theta_{zen} < 60^\circ\) as the observational criteria. We evaluate the detection conditions described in Section 3.2 on each sample taking into account the zenith angle dependence of the array performance (as shown in Section 3.3).

In this simulation, we consider only one array site and the GBM alerts (with its trigger rate of 250 yr\(^{-1}\)) alone. We limit our simulation to the GBM bursts with \(T_{90} > 2\) sec and \(z < 5\), the fraction of which is \(\sim 80\%\) of all GBM bursts. Note that this criterion does not greatly affect our final result of the detection rate. One of the reasons is that the trigger rate of short GRBs (\(T_{90} < 2\) sec) and high-redshift GRBs (\(z > 5\)) is typically smaller than the total trigger rate. Second, it is nearly impossible to start followup observations of short GRBs within their duration of prompt emission since it takes more than 2 sec to receive
the positional information from satellites. In addition, short bursts have smaller fluences than the long bursts, which will make the localization of the short GRBs with GBM more difficult. Finally, detection rate of the high-redshift GRBs is expected to be smaller (especially for afterglows) due to the severe EBL attenuation of gamma rays.

Hereafter, we classify generated GRB samples into several sets, in accordance with steps from the trigger by GBM to the detection by CTA:

- **Alert**: GRB samples that are detected by GBM and satisfy $T_{90} > 2$ sec and $z < 5$.
- **CTAobs**: Samples belonging to Alert whose positions are determined within zenith angle $\theta_{\text{zen}} < 60^\circ$ with the error radius $\sigma$ smaller than $\sigma_{\text{th}}$. Moreover, the CTA duty cycle of 10 % is also taken into account to select the samples of this class.
- **Pobs**: Samples belonging to CTAobs which satisfy the criterion $T_{\text{delay}} < T_{90}$.
- **Pdet**: Samples belonging to Pobs which are actually located within the FOV of LSTs and their prompt emissions are detectable by LSTs.
- **Adet**: Samples belonging to CTAobs which are actually located within the FOV of LSTs and their afterglows are detectable by LSTs.

LSTs makes observations for the **CTAobs** bursts.

### 4.1 Detection rate in the fiducial case

First, we show results of the detection rate with LSTs for our fiducial case in which we assume: (1) only the Band component for the prompt spectrum, i.e., no extra hard component ($R_{\text{extra}} = 0$), (2) GRBs whose high-energy photon index of the Band component is $\beta < -2$, (3) for the afterglow emission, the temporal index $p_t$ of $-1.5$ and the spectral energy index $p_{\gamma}$ of $-1$, (4) the EBL model provided by Razzano et al. (2009), (5) the typical delay time of starting observation, $T_{\text{delay}}$, of 100 sec and $\sigma_{\text{delay}}$ of 0.4 dex, and (6) the threshold value of the error radius $\sigma_{\text{th}}$ of 3.5° to start the follow-up observations. The dependence of the detection rate on parameters related to the LST performance and GBM emission is quantitatively discussed in later subsections.

#### 4.1.1 Prompt emission

With the above assumptions, we obtain 0.03 yr\(^{-1}\) as the detection rate of the GRB prompt emission with LSTs (see the first line in Table 1). Factors reducing the rate of Alert to that of Pdet are as follows. Among the samples belonging to Alert ($\sim$ 200 yr\(^{-1}\)), 21 % (i.e., 43 yr\(^{-1}\)) are localized enough to be followed-up by LSTs (see Section 3.1). Moreover, imposing $\theta_{\text{zen}} < 60^\circ$ and duty cycle of 0.1 we get 1.1 yr\(^{-1}\) for CTAobs sample. Of these, Pobs GRBs are 0.45 yr\(^{-1}\), and 6 % of Pobs GRBs belong to Pdet. Note that only one array site and only the alerts from GBM are assumed in this calculation. We discuss more general cases in Section 5.

In Figure 4 we show the cumulative distributions $P(> N_\gamma)$ of the total photon counts $N_\gamma$, where $N_\gamma$ is calculated by integration over $E_{\text{low}} < E < 300$ GeV. The red solid curve shows Pdet samples for the fiducial case. Once the prompt emission is successfully observed, we can expect the photon counts $N_\gamma > 10^2$ with the probability of 60 %. We also calculated the photon counts ($> 1$ GeV) expected for Fermi/LAT, and compared with $N_\gamma$. Then it is found that CTA/LSTs can detect 10–100 times more GeV photons than LAT for almost all the Pdet samples. Therefore CTA can provide the temporal and the spectral structure of high-energy emission of GRBs with higher significance than any other current instruments.

Figure 5 shows the redshift distribution of Pdet samples for the fiducial case with the red solid line in the form of the PDF. We found that for Pdet, $z \sim 1.5$ is typically expected and 90 % have redshifts less than 3.5. These results are little influenced by our limitation of $z < 5$, while it can depend on the assumed EBL model. Again we find that the difference in the redshift distribution between the model of Kneiske et al. (2004) and that of Razzano et al. (2009) is very small (see also Table 2 with regard to the detection rate). For comparison, we show the result for CTAobs samples (that have not been selected by the CTA performance) with black dotted line. We can see that the distribution of CTAobs is close to that of Pdet, which implies that the redshift distribution of Pdet events is mainly determined by the GBM sensitivity.

#### 4.1.2 Afterglows

The detection rate of the afterglow is obtained as 0.13 yr\(^{-1}\). Among CTAobs samples, 12 % satisfy detection criteria. Detection of the afterglow are expected for $\sim$ 84 % of GRBs whose prompt emission is detectable. Table 1 summarizes the results for our fiducial model assumptions. A similar estimate for the SVOM satellite will be presented in Section 4.5.

In Figure 5 blue dash-dotted lines show the redshift distribution of the Adet samples. We can expect typically $z \sim 1$ for Adet. It is found that the peak of the distribution of Adet samples is shifted toward lower $z$ from the distribution of CTAobs samples. This implies that in contrast to Pdet, low-$z$ samples are selected by the CTA sensitivity. We found that 90 % of Adet samples have redshifts less than 2.9.
Table 1. Expected event rates for one array site. We separately consider the cases in which each of Fermi/GBM and SVOM/ECLAIRs are the alerting detectors. Our fiducial model parameters are assumed. Each class is defined as follows: (Alert) Samples of GRBs that are detected by GBM and satisfy $T_{90} > 2$ sec and $z < 5$; (CTAobs) GRB samples belonging to Alert whose positions are determined within zenith angle $\theta_{\text{zen}} < 60^\circ$ with an accuracy of $\sigma < 3.5^\circ$. Moreover, we take into account CTA duty cycle of 10% to select CTAobs samples; (Pobs) GRB samples belonging to CTAobs which satisfy the criterion $T_{\text{delay}} < 90$; (Pdet) GRB samples whose prompt emissions are detectable by LSTs; (Adet) GRB samples whose afterglow emissions are detectable by LSTs.

|                  | Alert  | CTAobs | Pobs  | Pdet | Adet  |
|------------------|--------|--------|-------|------|-------|
| Fermi/GBM [yr$^{-1}$] | $\sim 200$  | 1.1    | 0.45  | 0.03 | 0.13  |
| SVOM/ECLAIRs [yr$^{-1}$] | $\sim 56$     | 2.0    | 0.65  | 0.1  | 0.37  |

4.2 Dependence on delay time distribution

In Figure 6, we show the dependence distributions of the GRB detection rate on the typical delay time, $\tau_{\text{delay}}$, which is introduced in Section 3.2. The top and the bottom panels represent cases for the prompt emission and the afterglow, respectively. In both panels, the horizontal axis represents $\tau_{\text{delay}}$, whereas the vertical axis shows the ratio of the detection rate to that for the fiducial parameter set. Hence, in both panels, the curves labeled as fiducial have the ratio of 1 if $\tau_{\text{delay}} = 100$ sec.

First, let us consider the prompt emission (the top panel of Figure 6). The red solid curve represents the fiducial case except for $\tau_{\text{delay}}$. If $\tau_{\text{delay}} = 60$ sec for LSTs, the detection rate is enhanced by a factor of 1.3. The light-blue dashed curve shows the result for the case where the extra component with $R_{\text{extra}} = 0.1$ is added to a spectrum of the prompt emission in all GRB samples. In this case, independently of $\tau_{\text{delay}}$, the detection rate is doubled compared to our fiducial case ($R_{\text{extra}} = 0$). In addition, to see the influence of the dispersion of $T_{\text{delay}}$, we draw the magenta dotted curve for the extreme case of no dispersion, i.e., $T_{\text{delay}} = \tau_{\text{delay}}$ for all events. At $\tau_{\text{delay}} = 90$ sec where it is comparable to the peak of the $T_{90}$ duration distribution of CTAobs GRBs, the two lines cross each other. If $\tau_{\text{delay}} \gtrsim 90$ sec, the dispersion makes the events with $T_{\text{delay}}$ smaller than the central value $\tau_{\text{delay}}$, which enhances the detection rate. On the other hand, if $\tau_{\text{delay}} \lesssim 90$ sec, the dispersion makes the events with $T_{\text{delay}}$ larger than the central value $\tau_{\text{delay}}$, which reduces the detection rate.

Next, let us consider the afterglow (the bottom panel of Figure 6). As the red solid curve in the top panel, the blue solid curve is for the fiducial case except for $\tau_{\text{delay}}$. This curve is for the afterglow temporal index $p_t$ of $-1.5$, while the brown dot-dashed and the pink dashed curves are for...
\[ p_i = -1.3 \text{ and } -1.8, \] respectively. These suggest that for the afterglow detection, the important factor is not \( T_{\text{delay}} \) but others such as the well-localized alert rate and the low-energy sensitivity.

The detection rate of the prompt emission is more sensitive to \( \tau_{\text{delay}} \) than that of the afterglow as shown in Figure 6. This simply comes from the fact that \( T_{\text{delay}} \) affects the number of \( P_{\text{obs}} \) bursts that satisfy \( T_{\text{delay}} < T_{90} \). To see this explicitly, we show in Figure 7 the \( T_{\text{delay}} \) distributions of \( CTA_{\text{obs}} \), \( P_{\text{obs}}, P_{\text{det}} \) and \( A_{\text{det}} \) in our fiducial case. We can see that the \( T_{\text{delay}} \) distribution of \( P_{\text{det}} \) is about the same as that of \( P_{\text{obs}} \), and they are shifted toward the shorter \( T_{\text{delay}} \) from that of \( CTA_{\text{obs}} \). On the other hand, the distribution of \( A_{\text{det}} \) is only slightly off set from that of \( CTA_{\text{obs}} \). In the afterglow case the condition \( T_{\text{delay}} < T_{90} \) is not required.

Although shortening \( \tau_{\text{delay}} \) to less than 100 sec does not have much impact on the improvement of the detection rate, we should note that shorter delay time is necessary for detecting the prompt emission. Because the minimum cutoff of \( T_{\text{delay}} \) is fixed to be 20 sec in our simulation, even when opposite, \( \tau_{\text{delay}} \) is assumed, shorter \( T_{\text{delay}} \) plays a significant role as mentioned above in the explanation of \( \sigma_{\text{delay}} = 0 \). Actually, in the bottom panel of Figure 7 for \( \tau_{\text{delay}} = 100 \text{ sec} \), we can see that \( T_{\text{delay}} \) is distributed at less than \( \sim 100 \text{ sec} \) in most cases where the prompt emission is detectable. Therefore it is crucial to keep the delay time as short as possible if the duration of the bursts in the CTA band and in the GBM band are similar to each other. In order to reduce \( T_{\text{delay}} \), fast alerts with good localization is equally important to a rapid slewing of LSTs. As an example, we simulate the case in which \( T_{\text{delay}} \) can not be shorter than 100 sec with the other parameters fixed to the fiducial values, and find that the detection rate of the prompt emission decreases by a factor of 2 in this case.

4.3 Dependence on the criterion of the error radius to start follow-up observations

One of the criteria for LSTs to start follow-up observations concerns \( \sigma_{\text{th}} \), whose fiducial value is set to 3.5° (see Section 4.1). Most of the GBM alerts have the error radius larger than this fiducial value. The larger \( \sigma_{\text{th}} \) we use, the more chances of the follow-ups we have, while the efficiency of the detection decreases. This is because the bursts with larger error radii are less probable to lie in the FOV of the LSTs.

In Figure 8 we show the dependence of the detection rate on \( \sigma_{\text{th}} \). The results are shown as the ratio to the fiducial case. The red solid line (\( P_{\text{det}} \)) and the blue dot-dashed line (\( A_{\text{det}} \)) show the increase in the detection rate by a factor of 1.2–1.3 for \( \sigma_{\text{th}} = 5° \) compared to 3.5°. On the other hand, one should keep in mind that the more rapid increase of \( CTA_{\text{obs}} \) (black dotted line) shows the decline in the detection efficiency (i.e., the ratio of \( P_{\text{det}} \) or \( A_{\text{det}} \) to \( CTA_{\text{obs}} \)) by a factor of 0.6–0.7. On the contrary, if we take \( \sigma_{\text{th}} \) to be less than 3.2°, most of the GBM alerts do not satisfy this criterion, so that the detection rate decreases very rapidly.

It can be seen from Figure 8 that the detection rates of \( P_{\text{det}} \) and \( A_{\text{det}} \) saturate around \( \sigma_{\text{th}} = 5° \), so that it seems better to set \( \sigma_{\text{th}} \) to near this value as long as we take a simple strategy of the follow-up observations, i.e., all 4 LSTs point toward the centroid of the GBM error circle.

![Figure 7](image-url)  
*Figure 7.* The delay time distributions for each class in the case of our fiducial parameter set (see Section 4.1 or Table 1 for explanation of classification for our samples). The bottom panel and the top panel are in the form of the cumulative distributions and \( \text{d}N/\text{d}(\log T_{\text{delay}}) \) normalized as \( N = 1 \), respectively. Each line represents the different class: for \( CTA_{\text{obs}} \), the black dotted line; for \( P_{\text{obs}} \), the black dashed line; for \( P_{\text{det}} \), the red solid line; and for \( A_{\text{det}} \), the blue dot-dashed line.

![Figure 8](image-url)  
*Figure 8.* Dependence of the event rate on the threshold error radius \( \sigma_{\text{th}} \), which is one of the criteria for LSTs to start the follow-up observations introduced in Section 4.1. The results are shown as the ratio to our fiducial case. The red solid line represents the result for \( P_{\text{det}} \), the blue dot-dashed line for \( A_{\text{det}} \), and the black dotted line for \( CTA_{\text{obs}} \) (see Section 4.1 or Table 1 for explanation of classification for our samples).
Table 2. Parameter dependence of the detection rate for one array size of CTA/LSTs, where only GBM is assumed as the alerting detector. The cases other than the fiducial one are for those in which one of the model parameters takes different value from that of the fiducial parameter set (with the other parameters fixed). Note that the localization accuracy of GBM is estimated optimistically for the prompt emission phase compared to the current localization accuracy. See Section 4.4 for the explanations of each Case.

|                | fiducial | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 | Case 8 |
|----------------|----------|--------|--------|--------|--------|--------|--------|--------|--------|
| $P_{\text{det}}$ [yr$^{-1}$] | 0.03     | 0.04   | 0.04   | 0.06   | 0.02   | 0.11   | 0.15   | 0.10   | 0.19   | 0.03   |
| $A_{\text{det}}$ [yr$^{-1}$] | 0.13     | 0.14   | –      | –      | –      | 0.11   | 0.15   | 0.10   | 0.19   | 0.03   |

Figure 9. The results in Table 2 are plotted as the ratio of the detection rate for $P_{\text{det}}$ and $A_{\text{det}}$, respectively. The same plot but for the simulated LAT detection rate, which is expected as 12 yr$^{-1}$.

The results for $P_{\text{det}}$ and $A_{\text{det}}$ in our fiducial case, are shown with the filled circle for Case 2, 3, and 4.

4.4 Dependence on other parameters

Table 2 summarizes how the detection rate changes when one of our model parameters takes different values from that of the fiducial parameter set (with the other parameters fixed). Each column describes the result for different cases: (first column) The fiducial case. (Case 1) The typical delay time of the follow-up $\tau_{\text{delay}}$ is set to 60 sec. (Case 2) The case including $\beta > -2$ according to the BATSE observation. (Case 3) The extra spectral component of $R_{\text{extra}} = 0.1$ is assumed for all the samples. (Case 4) The EBL model by Kneiske et al. (2004) is used. (Case 5 and Case 6) The temporal index of the afterglow $p_t$ is taken as $-1.3$ and $-1.8$, respectively. (Case 7 and Case 8) The spectral energy index of the afterglow $p_E$ is taken as $-0.5$ and $-1.5$, respectively.

The detection rate for Case 3 is about twice as large as the fiducial case. This fact remains unchanged for different $\tau_{\text{delay}}$, which is represented in the top panel of Figure 9 with the light-blue dashed curve. This is because $R_{\text{extra}}$ of 0.1 makes the bursts with intrinsically soft Band spectrum with $\beta \lesssim -2.5$ detectable; these soft bursts account for about half of Alert and CTAobs samples. By contrast, $R_{\text{extra}} = 0.1$ has little influence on the photon-count distribution and the redshift distribution. Comparing Case 2 with Case 3, the latter shows a larger increase of the detection rate compared to the former. This simply reflects that the fraction of bursts with $\beta > -2$ is less than those with $\beta \lesssim -2.5$.

We also calculate the expected LAT detection rate of Case 2 and Case 3, and then obtain 24 yr$^{-1}$ and 14 yr$^{-1}$, respectively. The former is more than three times as large as the observed LAT rate for the bursts of $T_{\text{iso}} > 2$ sec and $\gamma < 5$ (about 7–8 yr$^{-1}$), which seems unrealistic. The calculated LAT event rate for our fiducial case and Case 3 are similar to each other and about 1.5–2.0 times as large as the observed one. These somewhat large rates appear to be consistent with the analysis by Beniamini et al. (2011), claiming the existence of the spectral softening below the LAT band in some of bright bursts, since we have not taken into account any spectral softening feature in our simulations. We discuss this point a bit more in Section 4.5.

In addition to the cases summarized in Table 2, we studied the dependence of the detection rate on the luminosity function (see Eq. 2 and 3), the normalization of the effective area, $f_A$ (see Section 5.3), and the low-energy end of the LSTs sensitivity, $E_{\text{low}}$ (see Eq. 10). For the luminosity function, we found that when one of the 6 parameters included is varied from the best fit value within its errors, the rate changes at most by a factor of $\sim 0.8–1.3$ for both $P_{\text{det}}$ and $A_{\text{det}}$. For $f_A$, we see its influence on the detection rate by varying the value from 0.3 to 3. At this time, as a function of $f_A$, the background count rate $R_{\text{bg}}$ shifts from about 0.03 Hz to 3 Hz to keep the sensitivity of our LSTs model consistent with the official one. We found that this range of $f_A$ changes the detection rate by a factor of $\sim 0.8$ for $P_{\text{det}}$, though the change of the $A_{\text{det}}$ rate is negligible. This reflects the fact that for non-detected prompt emissions, the detection conditions (1) and (2) (which are described in the last part of Section 3.2), have comparable importance, while for non-detected afterglows, the condition (2) is the most strict. Note that the expected photon counts $N_t$ can vary in proportion to $f_A$. For $E_{\text{low}}$, we see the detection rate for the various exponent of cosine in Eq. 10. By varying it from $-4.3$ to 0, we found that the detection rate changes by a factor of $\sim 1.0–1.2$ for $P_{\text{det}}$ and $\sim 0.9–1.1$ for $A_{\text{det}}$. Therefore the luminosity function, $f_A$, or $E_{\text{low}}$ is not more sensitive to the detection rate than the other source parameters.

4.5 CTA detection rate for SVOM GRBs

Finally, we roughly estimate the detection rate for the case of alerts from SVOM/ECLAIRs, whose launch before the CTA operation is being planned (Schanne et al. 2010) and which will provide well-localized alerts ($< 10^7$) of about 80 yr$^{-1}$ Paul et al. 2011). Here we assume that its dura-
tion distribution is the same as the Burst Alert Telescope (BAT) onboard Swift because the two detectors, ECLAIRs (4–250 keV) and BAT (15–150 keV, Sakamoto et al. 2007), cover a similar energy range. The Swift data on $T_{90}$ was taken from the web site (from GRB 041217 to GRB 110519A). 80 % of ECLAIRs GRBs are expected at $z < 0.4$ from Planck et al. (2011) and ~90 % of the BAT bursts are long GRBs. Hence we assume that the fraction of all GRBs triggering ECLAIRs that have $T_{90} > 2$ sec and $z < 5$ is 70 %. We set the delay time $T_{\text{delay}}$ of 80 sec for all bursts for simplicity, while we assumed typically $T_{\text{delay}} = 100$ sec for GBM. This is because the SVOM alerts are expected to be faster than the GBM ones (i.e., $< 1$ min (Schanne et al. 2010)).

With the above assumptions, we can estimate the fraction of well localized events for which $T_{90} > T_{\text{delay}}$ is $\approx 33 \%$ for long GRBs. It is qualitatively expected that the fraction of $P_{\text{det}}$ or $Adet$ to the bursts in the LST FOV localized by ECLAIRs is lower than that by GBM. The reasons for this are as follows: (1) ECLAIRs does not need high fluence for localization as much as GBM, which leads to a lot of burst samples with dim flux in the CTA band. (2) ECLAIRs has better sensitivity for softer bursts rather than the hard ones, which again leads to the small number of events detectable with CTA. Also, the redshift distribution of bursts localized by ECLAIRs shifts to higher redshift than that by GBM, so that larger fraction of events are severely affected by the EBL attenuation. In evaluating the fraction of $P_{\text{det}}$ or $Adet$ to the bursts in LST FOV quantitatively, we do not simulate in detail the follow-up observation of ECLAIRs bursts with CTA taking into account its performance, but we just assume that the efficiency is the same as the case of Swift/BAT – if BAT is assumed to be the burst trigger and its trigger threshold for peak photon flux is simply set to 0.4 ph s$^{-1}$cm$^{-2}$ in the 15–150 keV band (about 90 % of actually detected BAT bursts have their peak flux above this value), we obtain lower detection efficiency than the case of GBM by a factor of 0.54 for the prompt emission and 0.34 for the afterglow in the case of $\sigma_{\text{d}} = 3.5$, $\tau_{\text{delay}} = 80$ sec for BAT, and 100 sec for GBM. Additionally, we must consider that SVOM operations feature a bias of preferentially pointing toward the anti-solar direction, which increases the probability of follow-up observations with ground-based telescopes. We set the increase of the detection rate by a factor of 1.4 referring to Gilmore et al. (2010).

With the above assumptions we can estimate the CTA detection rate for alerts from ECLAIRs as $\approx 0.1$ yr$^{-1}$ for the prompt emission, while $\approx 0.37$ yr$^{-1}$ for the afterglow (see Table 1), which is about three times higher rate than GBM. Hence SVOM will probably become better for the detection of GRBs with CTA than Fermi. Note that the GBM localization accuracy is estimated optimistically for the prompt emission phase (see Section 5.1), and also note that, unless the SVOM alerts are transmitted to enough ground stations, the delay time of 80 sec for SVOM alerts turns out to be an optimistic assumption.

5 SUMMARY AND DISCUSSIONS

In this paper, we have presented the prospects for detection of GRBs with the LSTs of CTA, the most vital component for GRB observations with their fast slew capability and the best sensitivity at the lowest energies. We have modeled and simulated the follow-up observation of GRBs with $T_{90} > 2$ sec and $z < 5$ alerted by Fermi/GBM. Our GRB population is modeled according to a given luminosity function that is consistent with Swift observations together with well-known spectral correlations. We note the following strengths of our model: (1) It reproduces the fluence and duration distributions of GBM bursts (Figure 1). (2) The differential sensitivity of our model LSTs is consistent with the official one given by the CTA Consortium (2010) in the energy range less than a few 100 GeV (Figure 3). (3) The Fermi/LAT detection rate is predicted to be 12 yr$^{-1}$ for the bursts satisfying both $T_{90} > 2$ sec and $z < 5$, which is roughly consistent with the actual rate of 7–8 yr$^{-1}$.

Assuming Fermi/GBM alerts alone, our fiducial parameter set predicts the GRB detection rate with LSTs for one array site (i.e., north or south) as 0.03 yr$^{-1}$ for the prompt emission and 0.13 yr$^{-1}$ for the afterglow emission (Table 1). The expected event rates become larger when two array sites of CTA and additional alerts from SVOM/ECLAIRs are taken into account — if the array performance for the two sites are the same in the energy range less than a few 100 GeV, the detection rates go up to about 0.3 yr$^{-1}$ and 1 yr$^{-1}$ for the prompt and afterglow emissions, respectively, where we assume no overlap of FOVs of GBM and ECLAIRs.

Note that in the above estimates, we optimistically estimate the onboard-localization ability of GBM in the prompt phase, expecting improvement by the CTA era (see Section 5.1). For the afterglow emission, our treatment of the GBM localization ability hardly affects the rate estimation.

For our fiducial assumptions, once CTA succeeds in detecting the prompt emissions for GBM alerts, the total photon counts $N_\gamma$ are expected to be $> 10^5$ for 60 % of CTA detected events. Our simulation also shows that $N_\gamma$ is 10–100 times larger than the number of GeV photons expected by LAT for the same bursts. This suggests that CTA can obtain the time resolved light curve in the energy range greater than a few tens of GeV with higher statistics than ever before. We expect 90 % of the prompt burst detected by CTA to have redshifts less than 3.5, and 90 % of the afterglows to have less than 2.9. Because of the follow-up observation after the GBM alerts, the redshift distribution is more affected by the GBM sensitivity rather than that of CTA. Hence, more frequent detections of high-z prompt emission are expected for SVOM alerts.

Studying the dependence of the detection rate on our model parameters, we found the following results:

(i) For the prompt emission, if all GRB samples have the extra power-law component with luminosity 10 % of the Band component, the detection rate with CTA increases by a factor of 1.9.

(ii) For the afterglow, the spectral index has a relatively large effect on the detection rate. It decreases by a factor

\[^5\] http://swift.gsfc.nasa.gov/docs/swift/swiflesc.html

\[^6\] GBM requires higher fluence to localize bursts, so that the duration of the localized bursts tends to be longer than that of the detected bursts to some extent. This is responsible for smaller ratio of bursts with $T_{90} > T_{\text{delay}}$ to the localized bursts for BAT (i.e., 33 %) than that for GBM (i.e., 43 %).
of 3 with the extreme assumption that all bursts have the softer spectral energy index of $-1.5$, while in the harder case of $-0.5$, the rate increases by a factor of 1.5.

(iii) If the typical value of the delay time between the start of observations and the GRB trigger time is 1 min, the detection rate of the prompt emission increases by a factor of about 1.3 compared to our fiducial case. On the other hand, the rate of the afterglow depends slightly on the delay time. Although the shorter delay time does not have much effect on the enhancement of the detection rate itself, the ability of fast slewing ($\lesssim 100 \text{ sec}$) is necessary for catching the prompt emission.

(iv) It seems better to make follow-up observations for the alerts with the error radius of up to $\sim 5^\circ$, as long as all 4 LSTs simply point toward the best position localized by GBM, although the detection efficiency is decreased.

(v) The detection rate varies by less than 30\% for variation of the other parameters including those of the luminosity function.

Note that the LAT detection rate is estimated to be $14 \text{ yr}^{-1}$ in the case of (i), which is about 1.8–2.0 times as large as the observed LAT event rate. This discrepancy may be due to the existence of the spectral softening below the LAT band, suggested for subset of bright events (Beniamini et al. 2011). Our crude (but reasonable) LAT detection conditions, etc. Even if the spectral softening effect is a dominant cause, the detection rate with CTA is not necessarily expected to decrease from our results by a similar factor, 1–2, due to the following possible reasons. First, the spectral softening below the LAT band has been only suggested for some of bright bursts (Beniamini et al. 2011). CTA will be sensitive even for typical (less bright) bursts, which might not have the spectral softening. Second, the bursts with the steep Band component below the LAT band may be hardly detected by LAT, whereas they might have an extra hard component at $>10 \text{ GeV}$, which can be relevant for CTA. We have not taken into account such possibilities in our simulations, which remain as future work. In any case, CTA may clarify the properties of the extra hard component and spectral softening of the Band component, which would strongly constrain the prompt emission mechanism.

It is crucial to increase the alert frequency with good localization in order to achieve higher detection rates. Hence the improvement of the localization accuracy by future GRB alert facilities is important. Let us consider the alerting detector which has the same characteristics (e.g., sensitivity) as GBM except for the localization ability, and simply assume that the alerts from the detector have a constant error radius $\sigma$ for all the alerted bursts. First, in this case, we can use the localization error $\sigma$ less than the threshold $\sigma_{th}$, the probability of localization in the FOV gets higher, while the probability of follow-up observations do not vary ($\text{CTA}_\text{obs} \sim 5 \text{ yr}^{-1}$). The increase of the probability saturates at $\sigma \sim 1^\circ$, and then the detection rate of $\text{Pdet}$ and $\text{Adet}$ for this detector are enhanced to $\sim 0.2 \text{ yr}^{-1}$ and $\sim 1.2 \text{ yr}^{-1}$, respectively. It implies that future alerting detectors with the better localization ability are more desirable.

As countermeasures against the alerts with large localization error, two observing strategies are proposed: one is to point each LST at different directions in the GBM error circle, while the other is to scan the region instead of pointing one location. The optimal strategy for each observation can be determined by the estimate of the detection probability, which requires the information on the trigger (such as the degree of localization error, the brightness, the expected delay time, and the zenith angle). In order to perform this and to increase the chance of detection, we need more detailed study on the sensitivity for each strategy as a function of some important parameters (such as zenith angle, the extended FOV, scan speed, etc.), which remains as a future work.

In the VHE region, the future High Altitude Water Cherenkov (HAWC) Observatory mission (Abeysekara et al. 2011) may also detect GRBs with its large FOV ($\sim 15\%$ of all the sky) and high duty cycle ($\sim 100\%$), while the GRB spectrum may be difficult to determine by HAWC, because of its small effective area and low energy resolution at $\sim 30 \text{ GeV}$ compared to CTA (Goodman et al. 2011). Hence, CTA and HAWC are complementary and both types of observations are important.

Very recently, Gilmore et al. (2011) and Bouvier et al. (2011) independently studied on expectations for GRB detection rates by CTA, and we find their results are broadly in agreement with our conclusions here.

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REFERENCES

Abdo, A.-A., et al. 2009a, Science, 323, 1688
Abdo, A.-A., et al. 2009b, 706, L138
Abdo, A.-A., et al. 2009c, ApJ, 707, 580
Abdo, A.-A., et al. 2009d, Nat., 462, 331
Abdo, A.-A., Ackermann, M., Ajello, M., et al. 2009, Phys. Rev. Lett., 102, 181101
Abdo, A.-A., Ackermann, M., Ajello, M., et al. 2010, ApJ, 712, 558
Abdo, A.-A., et al. 2010, ApJ, 734, L27
Abeysekara, A. U. et al. (HAWC Collaboration), 2011, arXiv:1108.6034
Ackermann, M., et al. 2010b, ApJ, 716, 1178
Ackermann, M., Ajello, M., Asano, K., et al. 2011, ApJ, 729, 114
Aharonyan, F. A., Akhperjanian, A. G., Barrio, J. A., et al. 1999, A&A, 342, 69
Aharonyan, F. A., Konopelko, A. K., V{"o}lk, H. J., & Quin- tana, H. 2001, Astroparticle Physics, 15, 335
Aharonyan, F.-A., Aharonian, F. A., Konopelko, A. K., V{"o}lk, H. J., & Quintana, H. 2001, Astroparticle Physics, 15, 335
Aharonyan, F.-A., et al. 2006, Science, 323, 1688
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Paul, J., Wei, J., Basa, S., & Zhang, S.-N. 2011, Comptes Rendus Physique, 12, 298
Pe’er, A., & Waxman, E. 2005, ApJ, 633, 1018
Pe’er, A. 2011, [arXiv:1111.3378]
Piran, T., & Nakar, E. 2010, ApJ, 718, L63
Razzaque, S., Dermer, C. D., & Finke, J. D. 2009, ApJ, 697, 483
Razzaque, S., Mészáros, P., & Zhang, B. 2004, ApJ, 613, 1072
Razzaque, S., Dermer, C.-D., & Finke, J.-D. 2010, OAJ, 3, 150
Rees, M.-J., & Mészáros, P. 1994, ApJ, 430, L93
Rees, M.-J., & Mészáros, P. 1998, ApJ, 496, L1
Rees, M.-J., & Mészáros, P. 2005, ApJ, 628, 847
Sakamoto, T., Hill, J. E., Yamazaki, R., et al. 2007, ApJ, 669, 1115
Salvaterra, R., et al. 2009, Nat., 461, 1258
Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
Schanne, S., Paul, J., Wei, J., et al. 2010, [arXiv:1005.5008]
Shao, L., & Ma, B-O. 2010, Mod. Phys. Lett. A, 25, 3251
Spruit, H. C., Daigne, F., & Drenkhahn, G. 2001, A&A, 369, 694
Takahashi, K, Murase, K., Ichiki, K., Inoue, S., & Nagataki, S. 2008, ApJ, 687, L5
Takahashi, K, Inoue, S., Ichiki, K., & Nakamura, T. 2011, MNRAS, 410, 2741
Tanvir, N.-R., et al. 2009, Nat., 461, 1254
Thompson, C. 1994, MNRAS, 270, 480
Toma, K., Ioka, K., Yamazaki, R., & Nakamura, T. 2006, ApJ, 640, L139
Toma, K., Wu, X.-F., & Mészáros, P. 2009, ApJ, 707, 1404
Toma, K., Sakamoto, T., & Mészáros, P. 2011a, ApJ, 731, 127
Toma, K., Wu, X.-F., & Mészáros, P. 2011b, MNRAS, 415, 1663
Totani, T. 1998, ApJ, 502, L13
Totani, T. 1998, ApJ, 509, L81
Uhm, Z.-L., & Beloborodov, A.-M. 2007, 665, L93
Wanderman, D., & Piran, T. 2010, MNRAS, 406, 1944
Wang, X.-Y., et al. 2009, ApJ, 698, L98
Wang, X.-Y., et al. 2010, ApJ, 712, 1232
Waxman, E. 1995, Phys. Rev. Lett., 75, 386
Vietri, M. 1995, ApJ, 453, 883
Yamazaki, R. 2009, ApJ, 690, L118
Yonetoku, D., Murakami, T., Nakamura, T., Yamazaki, R., Inoue, A. K., & Ioka, K. 2004, ApJ, 609, 935
Zhang, B. 2007, ChJAA, 7, 1
Zhang, B., & Yan, H. 2011, ApJ, 726, 90
Zhang, B., et al. 2006, ApJ, 642, 354

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