DETECTABILITY OF PAIR ECHOES FROM GAMMA-RAY BURSTS AND INTERGALACTIC MAGNETIC FIELDS

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Received 2008 June 25; accepted 2008 September 10; published 2008 October 3

ABSTRACT

High-energy emission from gamma-ray bursts (GRBs) can give rise to pair echoes, i.e., delayed inverse Compton emission from secondary electron-positron pairs produced in photon-photon interactions with intergalactic background radiation. We investigate the detectability of such emission with modern-day gamma-ray telescopes. The spectra and light curves are calculated for a wide range of parameters, applying the formalism recently developed by Ichiki et al. The flux depends strongly on the unknown magnitude and coherence length of intergalactic magnetic fields, and we delineate the range of field strength and redshift that allow detectable echoes. Relevant uncertainties such as the high-energy cutoff of the primary gamma-ray spectrum and the intensity of the cosmic infrared background are addressed. GLAST and MAGIC may be able to detect pair echo emission from GRBs with redshift ≤1 if the primary spectra extend to ~10 TeV, offering a unique probe of intergalactic magnetic fields.

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

Online material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs) are expected to be emitters of high-energy gamma rays, possibly up to TeV energies and above. Such TeV photons can interact with photons of the cosmic infrared background (CIB) to produce electron-positron pairs, which in turn generate inverse Compton (IC) gamma rays in the 1–100 GeV range that arrive with a characteristic time delay. Hereafter we shall call such delayed secondary emission “pair echoes.” One important implication of pair echoes is that their observation can indirectly probe the primary GRB spectra in the TeV range, even for distant bursts from which TeV photons are significantly attenuated during intergalactic propagation.

So far, observational data on high-energy gamma rays from GRBs has been limited. Although GeV emission was detected from several GRBs by EGRET (Dingus 2003 and references therein), firm detections have yet to be achieved at TeV energies (e.g., Atkins et al. 2005; Albert et al. 2007; Horan et al. 2007; Tam et al. 2007). Theoretical expectations for the high-energy component depend strongly on the emission mechanism and the physical parameters. In the conventional, internal shock model of the prompt emission attributed to synchrotron radiation from electrons, TeV gamma rays can be produced via leptonic (e.g., Papathanassiou & Meszaros 1996; Guetta & Granot 2003; Pe’er & Waxman 2004) and/or hadronic mechanisms (e.g., Totani 1998; Asano & Inoue 2007; Murase et al. 2008a; Asano et al. 2008b). Such gamma rays can avoid internal $\gamma$-$\gamma$ absorption and escape the source if the emission radius and/or bulk Lorentz factor are large enough (e.g., Razzaque et al. 2004; Murase & Ioka 2008). Hence, as long as the internal shock model is valid, we may expect that at least some fraction of GRBs have spectra extending into the TeV domain.

Plaga (1995) proposed that intergalactic magnetic fields (IGMFs) can be probed through observations of pair echoes because their delay time and flux depend strongly on the strength of intervening magnetic fields. Subsequent studies indicated that pair echoes from GRBs may be sensitive to IGMFs as small as $\sim 10^{-20}$ G (Dai & Lu 2002; Wang et al. 2004; Razzaque et al. 2004; Ando 2004; Casanova et al. 2007; Murase et al. 2007). Ichiki et al. (2008, hereafter IIT08) recently developed a new analytic formulation of pair echoes that properly incorporates the geometrical effects of photon propagation paths on the time delay, allowing more accurate calculations of the spectral evolution compared to previous, simpler analyses (e.g., Dai et al. 2002).

Pair echoes may be the only available tool to probe such tiny IGMFs, while other methods using Faraday rotation or the cosmic microwave background (CMB) are only sensitive to fields of order 1 nG. Weak IGMFs have actually been predicted to arise through various mechanisms at different epochs in the early universe, e.g., during cosmic inflation (Turner & Widrow 1988; Bamba & Sasaki 2007), recombination (Matarrese et al. 2005; Takahashi et al. 2005; Ichiki et al. 2006; Takahashi et al. 2008) or reionization (Gnedin et al. 2000; Langer et al. 2005). Constraints on the IGMF would also be crucial for understanding the origin of galactic magnetic fields (Widrow 2002).

GeV–TeV gamma-ray astronomy is currently undergoing rapid development, spurred on by ground-based telescopes such as MAGIC, H.E.S.S.,VERITAS, CANGAROO III, MILAGRO, etc., as well as the space-borne observatories GLAST and AGILE. Here we discuss in some detail the detectability of GRB pair echoes by such modern facilities, focusing on GLAST and MAGIC. Several conditions must be met: (1) the GRB must emit sufficiently strong, primary TeV gamma rays; (2) the pair echo flux must exceed the detector sensitivity; and (3) the pair echo must not be masked by other delayed emission components such as afterglows. Regarding point 1, given the uncertainties in the prompt emission physics, here we simply take the maximum cutoff energy $E_{\text{cut}}$ of the primary spectrum to be a parameter. Point 3 is commented on in § 4. Our main concern here is point 2. Besides the distance to the GRB and the properties of the IGMF, the pair echo flux depends on the primary emission spectrum as well as on the intensity of the...
CIB. Employing the formalism of IIT08, in this Letter we study how the detectability of pair echoes is affected by the IGMF, GRB distance, observed energy band, and observation time, together with uncertainties in \( E_{\text{cut}} \) and the CIB model, in a more systematic manner compared to previous studies. (See also Murase et al. [2008b] for application of the IIT08 formulation to blazar flares.)

## 2. Pair Echo Emission

Let us summarize the basic elements of pair echo emission from high-energy gamma-ray sources. A primary gamma ray with energy \( E \gtrsim 1 \) TeV emitted from a source interacts with an ambient CIB photon to create an electron-positron pair with mean free path \( \lambda_{\gamma \gamma} = 1/(0.26 \sigma_\gamma n_{\text{CIB}}) = 19 \) Mpc \((n_{\text{CIB}}/0.1 \text{ cm}^{-3})^{-1} \), where \( \sigma_\gamma \) is the Thomson cross section and \( n_{\text{CIB}} \) is the CIB photon density. The created pair energies have typical mean free paths \( E_p \approx E/2 \) and upscatter ambient CMB photons to produce secondary gamma rays whose average energy is \( (E_{\text{delay}}) = 2.77 T_{\text{CMB}}\gamma_c = 2.5 \text{ GeV}(E/2 \text{ TeV})^2 \), where \( \gamma_c = E/m_e c^2 \) is the Lorentz factor of the pairs and \( T_{\text{CMB}} = 3 \) K is the CMB temperature (CIB upscattering is neglected; cf. Murase et al. 2007).

If the energy range of the primary gamma rays is \( 1-10 \) TeV, the typical energy range of the pair echo emission is \( 1-100 \) GeV. The IC mean free path of the pairs is \( \lambda_{\text{IC,scat}} = 1/(\sigma_\gamma n_{\text{CMB}}) = 1.2 \) kpc, where \( n_{\text{CMB}} \approx 420 \) cm\(^{-3} \) is the CMB photon density. The pairs upscatter CMB photons successively until they lose most of their energy after propagating an IC cooling length \( \lambda_{\text{IC,cool}} = 3 m_e^2/4E \sigma_\gamma U_{\text{CMB}} = 350 \) kpc \((E/1 \text{ TeV})^{-1} \), where \( U_{\text{CMB}} \) is the CMB energy density.

The time delay in pair echoes is caused by the effects of angular spreading in pair production and IC interactions, as well as the deflections of the pairs in IGMMFs. The direction of the upscattered secondary photons deviates from the directions of the parent electron or positron and the primary gamma ray by angles \( \sim 1/\gamma_c \), so the typical delay time due to angular spreading can be estimated as

\[
\Delta t_{\text{ang}} \sim \frac{1}{2 \gamma_c} (\lambda_{\gamma \gamma} + \lambda_{\text{IC,cool}}) \\
\sim 3 \times 10^3 \text{s} \left( \frac{E_{\text{delay}}}{1 \text{ GeV}} \right)^{-1} \left( \frac{n_{\text{CIB}}}{0.1 \text{ cm}^{-3}} \right)^{-1}.
\]

Magnetic fields in the propagation region of the pairs gives rise to further deflections. For weak fields with coherence length \( r_{\text{coh}}(< \lambda_{\text{IC,cool}}) \), the variance of the magnetic deflection angle is \((\langle \theta_{\text{random}}^2 \rangle)^{1/2} = (\lambda_{\text{IC,cool}}/\sigma_\gamma r_{\text{coh}})^{1/2} = 2.2 \times 10^{-6} (E/1 \text{ TeV})^{-1/2} (B/10^{-18} \text{ G})(r_{\text{coh}}/100 \text{ pc})^{1/2} \), where \( r_s = 1.1 \text{ Gpc}(E/1 \text{ TeV})(B/10^{-18} \text{ G})^{-1} \) is the Larmor radius. The typical delay time due to magnetic deflections is

\[
\Delta t_B = \frac{1}{2} (\lambda_{\gamma \gamma} + \lambda_{\text{IC,cool}}) (\theta_{\text{random}}^2) \\
\approx 2 \times 10^3 \text{s} \left( \frac{E_{\text{echo}}}{1 \text{ GeV}} \right)^{-3/2} \left( \frac{B}{10^{-18} \text{ G}} \right)^2 \\
\times \left( \frac{r_{\text{coh}}}{100 \text{ pc}} \right)^{-1} \left( \frac{n_{\text{CIB}}}{0.1 \text{ cm}^{-3}} \right)^{-1}.
\]

Note that studies prior to IIT08 had neglected the \( \lambda_{\gamma \gamma} \) term in this expression and underestimated \( \Delta t_B \) by 2–3 orders of magnitude. Regarding \( r_{\text{coh}} \), values of \( \sim 100 \text{ pc} \) are expected, for example, in scenarios of IGMMF generation by radiation drag effects at cosmic reionization fronts (Langer et al. 2005). Since \( r_{\text{coh}} \) appears only through the combination \( B^2 r_{\text{coh}} \), results for different \( r_{\text{coh}} \) can be obtained by a simple rescaling. The total delay time is roughly \( \Delta t = \max \{ \Delta t_{\text{ang}}, \Delta t_B \} \), and the magnetic field properties are reflected in the delay as long as \( \Delta t_{\text{ang}} < \Delta t_B \). The primary gamma rays have \( \gamma-\gamma \) mean free paths that are typically larger than the sizes of large-scale structure such as clusters or filaments, so they are likely to escape such structures hosting the GRB until interacting with CIB photons to produce pairs in intergalactic void regions, which could have remained free from magnetic contamination by astrophysical objects (e.g., Bertone et al. 2006).

The spectra and light curves of GRB pair echoes can be evaluated as follows. For a GRB with primary fluence \( dN_{\gamma \gamma}/dE_{\gamma \gamma} \), the time-integrated flux of secondary pairs during the GRB duration is

\[
\frac{dN_{\gamma \gamma}}{dE_{\gamma \gamma}}(E_{\gamma}) = 4 m_e \frac{dN_{\gamma \gamma}}{dE_{\gamma \gamma}}(E_{\gamma} = 2 m_e \gamma_{\gamma})(1 - e^{-\tau_{\gamma\gamma}(E_{\gamma} = 2 m_e \gamma_{\gamma})}),
\]

where \( \tau_{\gamma\gamma}(E_{\gamma}) \) is the optical depth to \( \gamma-\gamma \) pair production for gamma rays with energy \( E_{\gamma} \). The time-dependent spectrum of the pair echo is

\[
\frac{d^2N_{\gamma \gamma}}{dt dE_{\gamma}} = \int dE_{\gamma} \frac{dN_{\gamma \gamma}}{dt} dE_{\gamma} \frac{d^2N}{dt dE_{\gamma}},
\]

where \( d^2N_{\gamma \gamma}/dt dE_{\gamma} \) is the IC power from a single electron or positron, and \( dN_{\gamma \gamma}/dt \) is the total time-integrated flux of pairs responsible for the echo emission observed at time \( t_{\text{obs}} \) after the burst, related nontrivially to \( dN_{\gamma \gamma}/dt \), in equation (3). IIT08 evaluated this relation taking into proper account the relevant geometrical effects and the stochastic nature of magnetic deflections. Numerical integration is required to obtain the end results, but it can be roughly described by \( dN_{\gamma \gamma}/dt \gamma_{\gamma} = (\lambda_{\text{IC,cool}}/c \Delta t) dN_{\gamma \gamma}/dt \gamma_{\gamma} \) (Dai et al. 2002).

Typical spectra and light curves of pair echo emission from GRBs are shown in Figures 1 and 2. We assumed a power-law primary spectrum \( dN_{\gamma \gamma}/dE_{\gamma \gamma} \propto E_{\gamma \gamma}^{-\alpha} \) for \( 0.1 \) TeV \( < E_{\gamma \gamma} < E_{\text{cut}} = 10 \) TeV, total isotropic-equivalent energy \( E_{\gamma \gamma} = 10^{50} \text{ ergs} \), mean energy \( E_{\gamma \gamma} = 0.5 \times 10^{50} \text{ ergs} \), and the burst duration \( \Delta t_{\text{burst}} = 10^{3} \text{ s} \).

![Figure 1](image_url)
10^{53} \text{ erg}, and GRB duration $T' = 50$, similar to IIT08. For the CIB, we fiducially adopted the “best fit” model of Kneiske et al. (2002, 2004). The sensitivities of GLAST and MAGIC are also compared in Figure 2. As can be seen, a characteristic feature of pair echo light curves is the exponential decay with the timescale as in equation (2).

It is important to note that the total fluence of the pair echo is determined by the amount of absorbed primary gamma rays and does not depend on the IGMF properties, with the contrary is true for the pair echo flux which is roughly the fluence divided by $\Delta \tau$. Stronger IGMFs lead to a lower fluxes for the pair echo that are more difficult to observe. The maximum measurable amplitude depends on several factors such as the distance to the source and the detector sensitivity, and turns out to be typically $10^{-19}$ to $10^{-20}$ G. However, the pair echo emission itself is easier to observe for weaker IGMFs. Thus, we have both an upper bound and a lower bound for the measurable amplitude.

$$\frac{\Delta \tau}{\Delta t^A} = 1.5 \times 10^{-2} \left( \frac{E_{\text{echo}}}{1 \text{ GeV}} \right)^{1/2} \left( \frac{B}{10^{-18} \text{ G}} \right)^{-2} \left( \frac{r_{\text{coh}}}{100 \text{ pc}} \right).$$

Depending on $r_{\text{coh}}$, the minimum measurable amplitude is expected to be $10^{-18}$ to $10^{-20}$ G. However, the pair echo emission itself is easier to observe for weaker IGMFs. Thus, we have both an upper bound and a lower bound for the measurable amplitude.

### 3. DETECTABILITY OF PAIR ECHO EMISSION FROM GRBs

Besides the amplitude and coherence length of IGMFs, the pair echo flux is also affected by uncertainties in the CIB, the knowledge of which is still rather poor (Hauser & Dwek 2001). Kneiske et al. (2002, 2004) constructed several semiempirical models of CIB evolution in accord with optical and infrared observations of galaxies. In Figure 3, we compare pair echo spectra for their “best fit” model with those for their “low SFR” model with a lower CIB. The two models differ by a factor $\sim 2$ in CIB intensity, roughly covering the differences in model predictions in the literature (e.g., Primack et al. 2005; Stecker et al. 2006). Note that the latest high-energy observations of blazar spectra favor a low CIB near the lower limits from galaxy counts, subject to assumptions on the primary spectral shape (Aharonian et al. 2006; Albert et al. 2008). The CIB can influence pair echoes in different ways. A lower CIB density results in less absorption of primary gamma rays and less pair echo emission, but it also reduces the re-absorption of the pair echo itself by the CIB at the highest energies. Although not included here, the CIB photons may also be upscattered by the pairs and contribute to the echo emission for $E_{\text{delay}} \geq 10 \text{ GeV}$ and/or lower $E_{\text{delay}}$ at late times (Murase et al. 2007).

Another important uncertainty is $E_{\text{cut}}$. Also compared in Figure 3 is the case for $E_{\text{cut}} = 5 \text{ TeV}$. From the relation $E_{\text{delay}} = 2.77 T_{\text{CM}} r_{\text{coh}}^2 = 2.5 \text{ GeV}(E_{\text{cut}}/2 \text{ TeV})^2$, we see that a decrease in $E_{\text{cut}}$ substantially reduces the pair echo flux at early times. However, the dependence on $E_{\text{cut}}$ is rather weak at late times because lower energy primary photons become more important for the echo.

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4 See http://www-glast.stanford.edu/

5 See http://magic.mppmu.mpg.de/
In Figure 4 we show regions in the $z$-$B$ plane where the flux of pair echo emission exceeds the detector sensitivities in the time interval $t_{\text{obs}} = 10^{-5} - 10^{-7}$ s, varying the CIB model and $E_{\text{cut}}$. As apparent in equation (2), the delay time is shorter for higher energies so that MAGIC can probe stronger IGMFs than GLAST. Below $B \sim 10^{-10}$ G, the delay time is dominated by $\Delta t_{\text{mz}}$ or $T^*$ and the detectability of the pair echo above $\sim$ GeV does not depend on $B$. The dependence on $E_{\text{cut}}$ is strong for the higher energy range of MAGIC ($\geq 100$ GeV), while is weaker for the lower energy range of GLAST ($\leq 10$ GeV), as long as $E_{\text{cut}} \geq 1$ TeV. The figure summarizes the range of IGMF strengths that can be probed with GRB pair echoes for various redshifts. For our specific GRB parameters, $z \leq 1.0$ is required for detectable pair echo emission. Since $\sim 10\%$ of all GRBs may occur at $z \leq 1.0$ (e.g., Jakobsson et al. 2006), there may be a reasonable chance to probe IGMFs through observations of their pair echoes.

### 4. SUMMARY AND DISCUSSION

This Letter investigated the detectability of pair echo emission from GRBs with GLAST and MAGIC. Utilizing the formalism developed in Ichiki et al. (2008) the spectra and light curves of GRB pair echoes were calculated for different intergalactic magnetic fields, CIB models, and primary cutoff energies. We surveyed the range of redshifts and field strengths that lead to detectable echoes and found $z \leq 1$ to be favorable, as long as $E_{\text{cut}} \geq 1$ TeV. Pair echoes from relatively nearby GRBs may thus offer a unique probe of the properties of intergalactic magnetic fields.

An issue that was not addressed here is the potential masking of the pair echo emission by the high-energy component of the afterglow. Although yet to be confirmed observationally, GeV–TeV emission from afterglows is theoretically predicted on various grounds (Zhang & Meszaros 2004; Dermer & Atoyan 2006 and references therein). They are generally expected to decline with time as power laws, whereas pair echoes decay exponentially with a characteristic timescale dependent on the intergalactic magnetic field (§ 3). A more detailed assessment of the detectability may warrant consideration of the CIB upscattered component at late times. This and other aspects will be discussed in more depth in future work.

K. T., K. M., and K. I. are supported by a Grant-in-Aid for the JSPS fellowship. S. I. is supported in part by Grants-in-Aid for Scientific Research from the Ministry of E.C.S.S.T. (MEXT) of Japan, Nos. 19047004 and 19540283. S. N. is supported likewise by Nos. 19104006, 19740139, 19047004. The numerical calculations were carried out on the Altix3700 BX2 at the YITP in Kyoto University. This work was supported by the Grant-in-Aid for the Global COE Program “The Next Generation of Physics, Spun from Universality and Emergence” from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan.

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![Figure 4.—Detectable region of pair echo emission in the $z$-$B$ plane with GLAST and MAGIC for tangled magnetic fields with $r_m = 100$ pc. Pair echo emission is deemed detectable if the flux exceeds the detector sensitivity during $t_{\text{obs}} = 10^{-5} - 10^{-7}$ s after the burst. Solid and dotted lines are estimates with the “best fit” and “low SFR” CIB models, respectively. The dashed line is for MAGIC with $E_{\text{cut}} = 5$ TeV and the “best fit” CIB model. [See the electronic edition of the Journal for a color version of this figure.]](image-url)