1. INTRODUCTION

Magnetic fields are observed to be common in the structured regions of the universe, such as galaxies and clusters of galaxies. To interpret their microgauss field strengths, the precollapse seed fields in the intergalactic medium required by dynamo theories may be of order $10^{-20}$ G (Kulsrud et al. 1997). Various theoretical possibilities have been suggested for the origin of such large-scale, intergalactic magnetic fields (IGMFs). For example, primordial magnetic fields of $\sim 10^{-20}$ G may be generated during the cosmological QCD phase transition (Sigl et al. 1997). They can also be produced during the inflationary epoch if conformal invariance of electromagnetic interactions is broken (Turner & Widrow 1988). Density fluctuations before cosmic recombination inevitably give rise to weak IGMFs (Takahashi et al. 2005; Ichiki et al. 2006). The Biermann battery mechanism (Gnedin et al. 2000) or radiation drag effects (Langer et al. 2005) at cosmic reionization fronts can induce fields of $10^{-20}$ to $10^{-16}$ G. At low redshift, such weak IGMFs are expected to survive in intergalactic void regions, as they can remain uncontaminated by astrophysical sources such as galactic winds or quasar outflows (Furlanetto & Loeb 2001). Measurements of IGMFs would be crucial for understanding the origin of galactic magnetic fields.

One of the best-known tools to probe magnetic fields is Faraday rotation measurements, from which an upper limit of $10^{-19}$ G has been derived for the IGMF assuming correlation lengths $\sim 1$ Mpc (Kronberg 1994). A different approach suitable for probing very weak IGMFs is to utilize “pair echo” emission from transient very high energy (VHE) gamma-ray emitters such as blazars and gamma-ray bursts (GRBs) (Plaga 1995). Multi-TeV photons from distant sources are attenuated by pair-production interactions with the cosmic microwave background (CMB) and cosmic infrared background (CIB). The electron-positron pairs then up-scatter CMB and CIB photons by the inverse Compton (IC) process to produce secondary gamma rays, whose flux depends strongly on the IGMF. If it is stronger than $\sim 10^{-12}$ G, the formation of a very extended and nearly isotropic pair halo is unavoidable (Aharonian et al. 1994). On the other hand, if the IGMF is sufficiently weak, most of the secondary gamma rays will come from the direction of the source with some temporal and spatial spreading as pair echo, containing valuable information on the IGMF. Blazars are promising sources for this purpose, since they are observed to exhibit strong flares at multi-TeV energies with flux variations by a factor of $\geq 10$ over timescales of $\leq 1$ hr to months. Pair echo emission is typically expected at GeV energies, appropriate for the recently launched Gamma-ray Large Area Space Telescope (GLAST) satellite.

Here we reconsider pair echo emission from blazars by exploiting the formulation recently developed by Ichiki et al. (2008; see also Takahashi et al. 2008), which allows more satisfactory calculations of the time-dependent echo spectra compared to previous works (Dai et al. 2002; Fan et al. 2004). Since the pair echo emission can persist after the primary flare decays, it may be observable unless it is hidden by some quiescent emission. Furthermore, constraints on the IGMF are possible even in the case of GLAST nondetections. We demonstrate this using as examples the past flares from Mrk 501 in 2005 and from PKS 2155−304 in 2006. Further details of our methods and results will be described in a subsequent paper (K. Takahashi et al., in preparation).

2. EMISSION PROPERTIES

So far, 23 AGNs have been detected at energies $\geq 0.1$ TeV (Wagner 2008). Most of them belong to the high-frequency-peaked BL Lac subclass of blazars, characterized by spectral energy distributions with two maxima occurring in the X-ray and TeV gamma ray bands. The standard blazar model com-
pris supermassive black holes ejecting relativistic jets close to the line of sight. Owing to relativistic beaming, blazars exhibit rapid flux variations on timescales down to a few minutes, with strong TeV flares being the most extreme events.

The $\gamma\gamma$ optical depth of the CIB depends on gamma-ray energy, source redshift, and CIB intensity. For the CIB, we adopt here the “best-fit” and “low-IR” models of Kneiske et al. (2002, 2004) (see also Primack et al. 2005; Stecker et al. 2006). Note that recent observations of TeV blazars may point to a CIB resembling the low-IR model, close to the lower limits from galaxy count data (Aharonian et al. 2006; Albert et al. 2008; see, however, Stecker et al. 2007).

### 2.1. Pair Echo Emission

The total fluence of pair echo emission is determined by the $\gamma\gamma$ optical depth of the CIB and does not depend on the IGMF. Primary photons with energy $E_\gamma$ are converted to electron-positron pairs with Lorentz factor $\gamma_\gamma \approx 10^6 (E_\gamma/1 \text{ TeV})^{1/2} (1+z)$ in the local cosmological rest frame, which then upscatter CMB and CIB photons. CMB photons are boosted to energies $\sim 2.82k_B T_{\text{CMB}}/(1+z) \approx 0.63 (E_\gamma/1 \text{ TeV}) (1+z)^3$ GeV, where $T_{\text{CMB}} = 2.73(1+z) \text{ K}$ is the local CMB temperature. To evaluate the pair echo flux, we must consider various timescales involved in the process, such as the flare duration, angular spreading time, and the delay time due to magnetic deflections (Dai et al. 2002; Fan et al. 2004; Murase et al. 2007). These can be estimated as follows.

The angular spreading time is $\Delta t_{\text{ang}} \approx (1+z)\lambda_{\text{IC}}/2\gamma_\gamma^2 c$, where $\lambda_{\text{IC}} = (0.26\sigma_T n_{\text{CIB}})^{-1} \approx 20$ Mpc ($n_{\text{CIB}}/0.1$ cm$^{-3}$)$^{-1}$ is the local $\gamma\gamma$ mean free path in terms of the local CIB photon density $n_{\text{CIB}}$, and $\lambda_{\text{IC}} = 3m_e c^2/(4\pi\sigma_T U_{\text{CMB}}(z)) \approx 690$ kpc ($\gamma_\gamma/10^4$)$^{-1} (1+z)^4$ is the local IC cooling length in terms of the local CMB energy density $U_{\text{CMB}}$. At the energies of our interest, $\lambda_{\gamma\gamma} \approx \lambda_{\text{IC}}$ so that $\Delta t_{\text{ang}} \approx (1+z)\lambda_{\text{IC}}/2\gamma_\gamma^2 c \approx 960$ s ($\gamma_\gamma/10^4$)$^{-1} (n_{\text{CIB}}/0.1$ cm$^{-3}$)$^{-1} (1+z)$. For sufficiently small deflections in weak IGMFs with present-day amplitude $B_{\parallel 0} = B_{00}(1+z)^{-2}$ and coherence length $\lambda_{\text{coh}} = \lambda_{\text{IC}}(1+z)$, the magnetic deflection angle is $\theta_B = \max[\lambda_{\parallel}/\lambda_{\text{IC}}, (\lambda_{\parallel}/\lambda_{\text{IC}})^{1/2}]$, where $\lambda_{\parallel} = r_a c\tau_{\text{life}} B_{00}$ is the Larmor radius of the electrons or positrons. The delay time due to magnetic deflections is $\Delta t_{\text{magn}} \approx (1+z)\lambda_{\text{IC}}/\xi_{\gamma\gamma} \theta_B c/2c$. Note that prior to Ichiki et al. (2008), the $\Delta t_{\text{magn}}$ term here had been neglected and $\Delta t_{\text{ang}}$ underestimated by up to 2–3 orders of magnitude. For coherent magnetic fields with $\lambda_{\text{coh}} \approx \lambda_{\text{IC}}$, we have $\Delta t_{\parallel} \approx \max [6.1 \times 10^3 s(\gamma_\gamma/10^4)^{-1} (B_{00}/10^{-20} \text{ G})^2 (1+z)^{-5}, 1.6 \times 10^5 s(\gamma_\gamma/10^4)^{-1} (n_{\text{CIB}}/0.1$ cm$^{-3}$)$^{-1} (B_{00}/10^{-20} \text{ G})^2 (1+z)^{-5}]$. Implicit in the above discussion is that both $1/\gamma_\gamma$ and $\theta_B$ do not exceed $\theta_0$, the opening angle of the AGN jet; otherwise a significant fraction of photons or pairs will be deflected out of the line of sight and the echo greatly diminished.

Together with the flare duration $T$, the pair echo delay time can be estimated by $\Delta t_{\parallel} = \max [\Delta t_{\text{ang}}, \Delta t_{\text{magn}}]$. If $\Delta t_{\parallel}$ dominates, pair echo can serve as effective probes of weak IGMFs. For flaring blazars with $T \sim \Delta t_{\parallel}$, the pair echo emission is not detectable as $\sim \gamma_\gamma T d/2c \approx 0.86 \text{ GeV} (B_{00}/10^{-20} \text{ G}) (T/1 \text{ day})^{-1/2} (n_{\text{CIB}}/0.1$ cm$^{-3}$)$^{-1/2} (1+z)^{-2}$ for the case of coherent IGMFs. Such estimates were the basis of previous evaluations of the pair echo flux (Dai et al. 2002; Fan et al. 2004) but explicit descriptions of the time-dependent spectra were not possible without some ad hoc modifications (Murase et al. 2007). In contrast, the formulation of Ichiki et al. (2008) enables us to calculate the time-dependent spectra in a more satisfactory manner, particularly at late times, accounting properly for the geometry of the pair echo process.

### 2.2. Primary Emission Spectrum

First we consider the archetypal flaring blazar Mrk 501. Strong flares at energies up to 20 TeV were observed in 1997 by HEGRA (e.g., Aharonian et al. 1999). Similar strong flares were recently observed by MAGIC from 2005 May through July (Albert et al. 2007) during which the flux varied by an order of magnitude, and intranight variability was observed with flux-doubling times down to 2 minutes on the nights of June 30 and July 9. We focus on the strong flare of June 30.

The second example is PKS 2155–304, the brightest VHE blazar in the southern hemisphere (Aharonian et al. 2005a, 2005b). During June 2006, the average VHE flux observed by HESS was more than 10 times its quiescent value in 2003 (Aharonian et al. 2007). In particular, an extremely strong flare was observed on July 28, ~50 times brighter than the quiescent level, which we use as a template for calculating the pair echo emission. Only small spectral differences were found between the flaring and quiescent states, as opposed to other blazars that often reveal large spectral changes at different flux levels (Aharonian et al. 2007).

From a theoretical viewpoint, the intrinsic maximum energy $E_{\gamma\gamma}^{\text{max}}$ should reflect either the maximum energy of accelerated electrons or protons, or a cutoff due to internal $\gamma\gamma$ absorption. Although the true value of $E_{\gamma\gamma}^{\text{max}}$ is not yet known, the spectrum of Mrk 501 was observed to extend at least to ~20 TeV, so here we take $E_{\gamma\gamma}^{\text{max}} = 20$ TeV as a reasonable assumption. Concerning the emission mechanism, both leptonic and hadronic models have been proposed (see, e.g., Sikora & Madejski 2001; Böttcher 2006 for reviews). The synchrotron self-Compton (SSC) model is one of the most popular leptonic models (e.g., Maraschi et al. 1992; Inoue & Takahara 1996). Another frequently discussed leptonic model is the external Compton model, where electrons upscatter external photons originating outside the jet. In BL Lac objects, the tightly correlated variability in the X-ray and TeV bands (e.g., Katarzyński et al. 2005) and the lack of strong emission lines indicate a minor role for external photons and favor the SSC model. In hadronic models involving protons accelerated to ultrahigh energies, the high-energy spectra are attributed to synchrotron radiation from either the protons themselves (Aharonian 2000), or secondary electron-positron pairs generated in photodihadronic interactions (Mannheim 1993). The hadronic models are challenged by the observed X-ray–TeV correlation and rapid gamma-ray variability, but they have not been entirely ruled out.

### 3. RESULTS

Figure 1 shows the time-dependent pair echo spectra for the 2005 flare of Mrk 501 at different times $t$ after the onset of the flare, whose flux is assumed to decay as $\exp(-t/T)$ on a timescale $T = T/(1+z) \approx 0.5$ days. We take $\lambda_{\text{coh}} = 0.1$ kpc and different values of $B_{00}$. The sub-TeV primary spectrum of Mrk 501 is relatively hard with photon index $\alpha \approx 0.4$ (Aharonian et al. 2002; Albert et al. 2006). Extrapolating this to GeV, the pair echo should be visible relative to the primary flare. It should not be masked by the quiescent GeV emission either, if the latter is estimated by a one-zone SSC model consistent with the “low flux” TeV data of 2005 as in Figure 21 of Albert et al. (2007). Compared with the GLAST sensitivity, the detection prospects for pair echoes seem reasonable as long as the IGMF is sufficiently weak (see also Dai et al. 2002). Detailed observations of its spectra and light curve will provide
valuable information on the IGMF (K. Takahashi et al., in preparation).

Note, however, that Mrk 501 has been previously detected at GeV by EGRET during a multiwavelength campaign in 1996 March (Kataoka et al. 1999). The TeV spectrum was much harder than in 1997, and the entire GeV–TeV spectrum was incompatible with the simplest, one-zone SSC model. If this GeV emission corresponds to a persistent, quiescent component of Mrk 501, it may obscure the pair echo emission. This question should be resolved soon by GLAST.

Results for the 2006 flare of PKS 2155–304 are shown in Figure 2, with assumptions for the flare similar to Mrk 501. Here we fix \( B_\text{IG} = 10^{-20} \) G and show the dependence on \( \lambda_\text{coh} \). The case of \( \lambda_\text{coh} = 0.1 \) kpc corresponds to tangled IGMFs

\[
\log(E_2), \log(E_1) \text{[GeV]} \quad \text{[GeV/s]}
\]

![Figure 1](image1.png)

**Fig. 1.—** Pair echo spectra for the 2005 flare of Mrk 501, plotted at \( t = T = 0.5 \) day (thin lines) and \( t = 3T = 1.5 \) days (thick lines), for the cases of \( B_\text{IG} = 10^{-20} \) G (solid lines) and \( 10^{-18} \) G (dot-dashed lines) with \( \lambda_\text{coh} = 0.1 \) kpc. Also shown are the observed primary spectrum (thick dashed line) and intrinsic primary spectrum for the low-IR CIB model (thin dashed line) at \( t = 0 \), described by linear extrapolation at \( \lesssim 200 \) GeV. The quiescent emission is represented by an SSC model (dotted line). The GLAST sensitivity for integration time \( t = 3T = 1.5 \) day is overlaid. [See the electronic edition of the Journal for a color version of this figure.]

Next we discuss the lower limits that can be imposed on the IGMF even when GLAST does not detect pair echoes from TeV blazars. Such limits would be valid if the primary flare and quiescent emission at GeV energies are low enough so that the case of \( B_\text{IG} = 0 \) implies an excess of the echo flux \( dF_\gamma/dE_\gamma \) over the primary flux \( dF_\gamma/p dE_\gamma \). The nondetection of the echo emission can then be attributed to the effects of a finite IGMF, expressed as \( (dF_\gamma/p - dE_\gamma) \max ((dF_\gamma/p + dE_\gamma), (dF_\gamma/p - dE_\gamma)) \), where \( dF_\gamma/p \) and \( dE_\gamma \) is the GLAST sensitivity. Summarized in Table 1 are the constraints thus derived for the IGMF, which depend on the CIB as well as on assumptions for the primary emission. For PKS 2155–304, the limits are given

\[
\lambda_\text{coh} \leq \lambda_\text{GR}, \quad \lambda_\text{coh} = 1 \text{ Mpc}
\]

\[
(\lambda_\text{coh} \geq \lambda_\text{GR}).
\]

**Fig. 3.—** Primary and pair echo light curves for a hypothetical strong flare of PKS 2155–304 compared with the GLAST sensitivity at 1 GeV (solid lines) and 10 GeV (thin lines), for the case of \( B_\text{IG} = 10^{-20} \) G (solid lines) and \( B_\text{IG} = 0 \) G (dot-dashed lines) with \( \lambda_\text{coh} = 1 \) Mpc. The best-fit CIB model is employed. Also shown is the total primary light curve for both flare and quiescent emission assuming an SSC model. [See the electronic edition of the Journal for a color version of this figure.]

| Flare Source | CIB Model | Duration \( T \) (days) | Expected Lower Limit \( B_\text{IG} \) (G Mpc\(^{-1}\)) |
|-------------|-----------|-------------------------|----------------------------------|
| Mrk 501     | Low-IR    | 0.5                     | \( 10^{-20.5} \) |
|             | Best-fit  | 0.5                     | \( 10^{-19} \) |
| PKS 2155–304| Low-IR    | 0.5                     | \( 10^{-21.3} \) |
|             | Best-fit  | 0.5                     | \( 10^{-20.3} \) |

**TABLE 1**

**Lower Bounds on the IGMF in the Case of GLAST Nondetections of Pair Echoes**
only for the hadronic model, since the $B_{\parallel} = 0$ echo flux is not expected to exceed the primary flux for the SSC model. More conservative but less model-dependent constraints may be deduced for blazars such as Mrk 501 with hard primary TeV spectra, where the primary GeV emission is expected to be less obstructive (Fig. 1). Note that these limits are for tangled IGMF that lead to lower echo fluxes at $\leq 10$ GeV and hence more conservative limits compared to coherent fields. The same is true for low-IR models compared to best-fit models for the CIB. A more detailed account of the primary light curve should allow more realistic constraints.

4. SUMMARY AND DISCUSSION

We have evaluated the time-dependent spectra of secondary pair echo emission from TeV blazars and discussed the information that can be derived for the IGMF, applying a recently developed formalism of pair echoes that properly describes their time evolution. The observational prospects are quite interesting for the recently launched GLAST mission, and successful detections would open a new window on studies of cosmic magnetic fields. Even in the case of nondetections, lower limits on the IGMF of $B_{\parallel} \lesssim (10^{-19}$ to $10^{-21})$ G Mpc$^{-1}$ may be obtained, making use of suitably strong TeV flares with hard spectra. The existence of a weak but nonzero IGMF may also sometimes enhance rather than diminish the detectability of echo emission at late times.

Further detailed calculations utilizing Monte Carlo methods may be desirable for more robust predictions. For example, the effect of cooling of pairs during propagation in the IGMF can be moderately important, leading to fluxes smaller by a factor of several compared to the results given here (Murase et al. 2007). Also of concern are uncertainties in the CIB models, which can affect not only the pair echo fluence but also the timescales for angular spreading and magnetic deflection delay at all redshifts. We must also beware of uncertainties in the intrinsic primary spectra including the value of $E_{\gamma}^{\max}$.

In addition to pair echoes from flares, the quiescent emission of TeV blazars may also contain useful information on the IGMF. For example, depending on the CIB, the spectra corrected for $\gamma\gamma$ absorption for some blazars including Mrk 501 point to a sharp pileup at high energies, contradicting the expectations from conventional emission models. However, as long as $B_{\parallel} \lesssim 10^{-18}$ G and the primary spectra has photon index $\alpha \sim 2$ and $E_{\gamma}^{\max} \gtrsim 100$ TeV, an intergalactic cascade component may contribute to the quiescent TeV emission and compensate the effects of CIB absorption (Aharonian et al. 2002). The quiescent flux at $\lesssim \text{GeV}$ could also be affected by such cascades (Dai et al. 2002). These issues will be elaborated on in a future publication (K. Takahashi et al., in preparation).

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