Lower bounds are derived on the amplitude $B$ of intergalactic magnetic fields (IGMFs) in the region between Galaxy and the blazar Mrk 421, from constraints on the delayed GeV–pair–echo flux that are emitted by secondary $e^+e^−$ produced in $\gamma\gamma$ interactions between primary TeV gamma rays and the cosmic infrared background. The distribution of galaxies mapped by the Sloan Digital Sky Survey shows that this region is dominated by a large intergalactic void. We utilize data from long-term, simultaneous GeV–TeV observations by the Fermi Large Area Telescope and the ARGO-YBJ experiment extending over 850 days. For an assumed value of $B$, we evaluate the daily GeV pair-echo flux expected from the TeV data, select the dates where this exceeds the Fermi $2\sigma$ sensitivity, compute the probability that this flux is excluded by the Fermi data for each date, and then combine the probabilities using the inverse normal method. Consequently, we exclude $B < 10^{-20.5}$ G for a field coherence length of 1 kpc at $\sim 4\sigma$ level, as long as plasma instabilities are unimportant for cooling of the pair beam. This is much more significant than the $2\sigma$ bounds we obtained previously from observations of Mrk 501, by virtue of more extensive data from the ARGO-YBJ, as well as improved statistical analysis. Compared with most other studies of IGMF bounds, the evidence we present here for a non-zero IGMF is more robust as it does not rely on unproven assumptions on the primary TeV emission during unobserved periods.

Key words: BL Lacertae objects: individual (Mrk 421) – galaxies: active – gamma rays: general – magnetic fields – radiation mechanisms: non-thermal

Online-only material: color figures

1. INTRODUCTION

Intergalactic magnetic fields (IGMFs), particularly those inside intergalactic void regions, have attracted much interest as possible remnants of primordial magnetic fields that were generated in the early Universe (e.g., Gnedin et al. 2000; Langer et al. 2005; Takahashi et al. 2005; Ichiki et al. 2006). While such fields can be amplified later within galaxies and galaxy clusters by dynamo processes, they may remain unaffected by subsequent astrophysical effects such as diffuse cosmic microwave background. Thus, IGMFs are expected to be a window onto the early Universe. For comprehensive reviews on primordial and IGMFs, see Widrow (2002), Widrow et al. (2012), and Ryu et al. (2012).

However, the predicted amplitudes for IGMFs of primordial origin are generally very small, $B = 10^{-25}–10^{-15}$ G, and difficult to probe through Faraday rotation measurements in distant radio sources or their effects on the anisotropy of the cosmic microwave background (CMB). In this context, a method that is sensitive to weak IGMFs utilizing delayed secondary emission from high-energy gamma-ray sources was proposed by Plaga (1995) and subsequently developed by many authors (Dai et al. 2002; Razzacque et al. 2004; Murase et al. 2007, 2008; Ichiki et al. 2008; Takahashi et al. 2008, 2011; Elyiv et al. 2009; Neronov & Semikoz 2009). Such emission that we refer to as “pair echos” is expected to occur typically at GeV energies, for which the Fermi Large Area Telescope (LAT) is currently the most sensitive instrument. Since the echo flux is predicted to be larger for smaller $B$, a GeV upper limit on such components translates into a lower bound on $B$.

In our previous study (Takahashi et al. 2012), we focused on a specific TeV flare of Mrk 501 observed in 2009 by the VERITAS (Very Energetic Radiation Imaging Telescope Array System) and MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescopes. Comparing the expected light curves of the pair echo from the flare and the concurrent quiescent emission with simultaneous Fermi observations, we obtained a lower bound on the IGMF amplitude of $B > 10^{-20}$ G at 90% confidence level assuming a field coherence length of 1 kpc. This was obtained with minimal assumptions about the primary TeV emission during unobserved periods or spectral bands, and can be considered more robust in comparison with previous studies (Neronov & Vovk 2010; Ando & Kusenko 2010; Tavecchio et al. 2010, 2011, 2012; Dolag et al. 2011; Dermer et al. 2011; Neronov et al. 2011; Taylor et al. 2011; Arlen et al. 2012).

Here we focus on the TeV blazar Mrk 421 located at $z = 0.031$. As seen in Figure 1, maps of the local galaxy distribution from the Sloan Digital Sky Survey reveal that a large void lies between our Galaxy and the supercluster containing Mrk 421 (Abazajian et al. 2009; Blanton et al. 2005). This is also seen to be the case for Mrk 501. Thus, Mrk 421 is a desirable target for probing IGMFs. Mrk 421 has been monitored continuously at TeV energies by the ARGO-YBJ experiment over the period from 2007 November to 2010 February (Bartoli et al. 2011, hereafter B11), during which many flares were observed so that more statistically significant bounds on IGMFs can be expected. Note that compared with Cherenkov telescopes, such air shower detectors have a much higher duty cycle and allow uninterrupted long-term observations, albeit at lower sensitivity.
2. TeV AND GeV EMISSION FROM MRK 421

First we discuss the TeV spectrum and light curve of Mrk 421 with which we evaluate the pair echo. In B11, the daily fluxes at energies above 0.3 TeV are presented for approximately 850 days. For some days, negative numbers are reported that are presumably caused by systematic errors, and we simply set them to zero. Although the spectra are not available separately for each day, average spectra were derived for four different flux states based on the X-ray count rate. Since the TeV flux was shown to be tightly correlated with that in X-rays, here we choose to define three flux states according to the daily TeV counts, “high” (count > 80), “medium” (40 < count < 80), and “low” (count < 40), which correspond, respectively, to the X-ray flux levels 4, 3, and 1+2 of B11. Note that levels 1 and 2 can be treated together for our purposes as their TeV spectra are very similar. According to the daily flux, we assume that the TeV spectral index for each day takes the average value of the corresponding flux state. We also impose a maximum spectral cutoff at 5 TeV as the highest energy photons detected by ARGO-YBJ, as well as a minimum cutoff at 0.1 TeV.

For GeV gamma rays, we utilize the data from Fermi-LAT that has been performing continuous observations of Mrk 421 in the survey mode from MJD 54683. We obtained the data through the Fermi Science Support Center (FSSC) and adopt the standard analysis tools provided by the FSSC. In our analysis, we divide the energy band in three, that is, 100 MeV–1 GeV, 1–10 GeV, and >10 GeV, and derive flux probability distribution functions for each day assuming Poisson statistics. Because the statistics is small for this short interval (one day bins), we adopt the aperture photometry method where we count events located within 1° from the source. Note that we can neglect the background events above 1 GeV for this timescale at the high Galactic latitude of Mrk 421. Below, we use data during MJD 54683–55255, when both TeV and GeV observations were performed, focusing on the energy range of 1–10 GeV where Fermi-LAT is most sensitive and the strongest constraints on the pair echo can be obtained.

3. PAIR ECHO

We briefly summarize the basic physics of pair echos (for details, see, e.g., Ichiki et al. 2008 and Takahashi et al. 2012). The mean free path of primary gamma rays with energy $E_{\gamma} \gtrsim 1$ TeV for $\gamma\gamma$ interactions with the CIB is $\lambda_{\gamma\gamma} = 1/(0.26\sigma_T n_{IR}) = 190$ Mpc ($n_{IR}/0.01$ cm$^{-3}$)$^{-1}$, where $\sigma_T$ is the Thomson cross section and $n_{IR}$ is the number density of
relevant CIB photons. The interaction results in an $e^{-}e^{+}$ pair with energy $E_{e} \approx \frac{E_{\gamma}}{2}$, which can then inverse-Compton (IC) upscatter ambient CMB photons to produce the pair echo, that is, secondary gamma rays with energy ($E_{\text{echo}} = 2.7T_{\text{CMB}}\lambda_{\text{cool}}=2.5$ GeV ($E_{\gamma}/2$ TeV)$^{2}$, where $T_{\text{CMB}} = 2.7$ K is the CMB temperature and $\gamma_{c} = E_{e}/m_{e}c^{2}$. For primary gamma rays with $E_{\gamma} \approx 1-5$ TeV, $E_{\text{echo}} \approx 1-10$ GeV. As long as plasma instabilities are unimportant (see below), the pairs continue successive IC scattering until they lose a large fraction of their energy over a length scale $\lambda_{\text{IC,cool}} = \frac{3m_{e}^{2}}{(4E_{\gamma}\sigma_{T}U_{\text{CMB}})} = 350$ kpc ($E_{\gamma}/1$ TeV)$^{-1}$, where $U_{\text{CMB}}$ is the CMB energy density. Comparing typical values for $\lambda_{\gamma\gamma}$ and $\lambda_{\text{IC,cool}}$, we see that the pairs are generated mostly far away from the source, and then cool over a much smaller scale. Thus, for Mrk 421, the pairs are likely to be produced deep inside and propagate only within the large, intervening void (Figure 1).

It has been suggested recently that rather than IC cooling, the beam of the $\gamma\gamma$-produced pairs may lose much of their energy by heating the intergalactic gas through two-stream-like plasma instabilities (Broderick et al. 2012; Schlickeiser et al. 2012). If true, it may considerably reduce the pair-echo signal, while causing some non-trivial consequences for the evolution of galaxies and the intergalactic medium (Chang et al. 2012; Pfommer et al. 2012). However, the actual efficiency and eventual fate of such instabilities has been debated (Miniati & Elyiv 2013) and is highly uncertain at the moment. Below, we proceed on the assumption that such instabilities are insignificant.

A crucial attribute of the pair echo is the time delay compared with the primary gamma rays, caused by two effects. One is the angular spreading inherent in the pair production and IC scattering processes, for which the typical delay time $\Delta t_{\text{ang}} = (\lambda_{\gamma\gamma} + \lambda_{\text{IC,cool}})/2\gamma_{c}^{2} \approx 3 \times 10^{4}$ s ($E_{\text{echo}}/1$ GeV)$^{-1}(n_{\text{IR}}/0.01$ cm$^{-3})^{-1}$ (Ichiki et al. 2008). The second is deflections of the pairs in the IGMF with typical delay time $\Delta t_{B} = (\lambda_{\gamma\gamma} + \lambda_{\text{IC,cool}})/\langle \theta_{B}^{2} \rangle/2$, where $\langle \theta_{B}^{2} \rangle^{1/2} = \max[\lambda_{\text{IC,cool}}/r_{L}, (\lambda_{\text{IC,cool}}r_{\text{coh}}/6)^{1/2}/r_{L}]$ is the typical deflection angle, $r_{L}$ the Larmor radius and $r_{\text{coh}}$ the coherence length of the IGMF. If $r_{\text{coh}} / \lambda_{\text{IC,cool}}$, that is, the IGMF is sufficiently tangled on the IC cooling scale,

$$\Delta t_{B} \approx 2 \times 10^{4} s \left( \frac{E_{\text{echo}}}{1 \text{ GeV}} \right)^{3/2} \left( \frac{B/10^{-19} \text{ G}}{1 \text{ kpc}} \right)^{2} \left( \frac{r_{\text{coh}}/0.01 \text{ cm}^{-3}}{1 \text{ kpc}} \right)^{-1},$$

where $B$ is the field amplitude. Hereafter, we take a fiducial value $r_{\text{coh}} = 1$ kpc (see, e.g., Langer et al. 2005), although the results can be trivially scaled for other values as it always occurs in the combination $B^{2}r_{\text{coh}}^{-1}$. The total delay time is approximately $\Delta t_{\text{ang}} + \Delta t_{B}$, and the magnetic field properties are reflected in the delay as long as $\Delta t_{\text{ang}} \ll \Delta t_{B}$.

To calculate the pair-echo spectra and light curves, we follow Ichiki et al. (2008). First, the time-integrated flux of secondary pairs is

$$\frac{dN_{e,0}}{dy_{e}}(y_{e}) = 4m_{e} \frac{dN_{\gamma}}{dE_{\gamma}}(E_{\gamma} = 2m_{e}y_{e}) \left[1 - e^{-\tau_{\gamma\gamma}(E_{\gamma} = 2y_{e}m_{e})} \right],$$

where $dN_{\gamma}/dE_{\gamma}$ is the primary gamma-ray fluence and $\tau_{\gamma\gamma}(E_{\gamma})$ is the $\gamma\gamma$ optical depth in the CIB. The time-dependent pair-echo spectrum is

$$\frac{d^{2}N_{\text{echo}}}{dt\,dE_{\gamma}} = \int d\gamma_{e} \frac{dN_{e}}{dy_{e}} \frac{d^{2}N_{\text{IC}}}{dt\,dE_{\gamma}}.$$
the peak flux of the echo is larger and its response to the primary emission is quicker. Although the magnetic deflection implies that the pair-echo emission should also be spatially extended around the primary source, the extension is much smaller than the Fermi angular resolution and can be neglected for the field strengths of $B \sim 10^{-20}$ G considered here.

4. STATISTICAL ANALYSIS

We now compare the expected pair echo with the Fermi-LAT data and derive constraints on the IGMF. Compared with our previous paper (Takahashi et al. 2012), we have a much greater number of independent flux bins (each representing the daily count), so a more sophisticated method of deriving the constraints is necessary. First, we compute the probability $P_i$ that a specific value of the IGMF amplitude is excluded by the $i$th flux bin, using the probability distribution function of the true flux obtained from the Fermi-LAT observation. Then, we combine the probabilities to derive the total probability $P_{\text{tot}}$ using meta-analysis.

Note that it would not be appropriate to simply combine such probabilities for all bins. If the TeV flux for the $i$th bin is low enough for the expected echo flux to be below the Fermi sensitivity for that bin, the probability $P_i$ would be small, irrespective of $B$. If we combine all such probabilities, the total probability $P_{\text{tot}}$ can become so small that no constraints on $B$ can be obtained, even if some values of $P_i$ are sufficiently large for bins during TeV flares. Thus, we must select data bins for which the expected echo flux would be detectable by Fermi, depending on the assumed value of $B$. As explained above, larger $B$ results in a weaker echo that can only be detected for bins with higher TeV flux, so the number of such bins will be smaller. Here we set this selection threshold such that the echo flux exceeds the $2\sigma$ sensitivity of Fermi-LAT. In Figure 4, this is compared with the echo light curves for $B = 10^{-20.5}$ G and $10^{-20}$ G at 1–10 GeV during a particular 50 day period (only a small fraction of the entire data set). Here four and three bins exceed the Fermi-LAT sensitivity for $B = 10^{-20.5}$ G and $10^{-20}$ G, respectively, which correspond to large TeV flares as seen in Figure 3.

Figure 4 also plots the 50% confidence Fermi-LAT upper limits on the daily flux. For the first flare (MJD 55147), the expected pair-echo flux for $B = 10^{-20.5}$ G greatly exceeds the upper limit, and the probability that this value of $B$ is excluded is very large. Although that for $B = 10^{-20}$ G also exceeds the limit, it does not reach the $2\sigma$ sensitivity, so the bin is not counted to compute $P_{\text{tot}}$ for this $B$ value. For the second (MJD 55152) and third (MJD 55166) flares, the echo fluxes surpass the upper limits as well as the sensitivity for both $B = 10^{-20.5}$ G and $10^{-20}$ G. For the fourth flare (MJD 55182), the echo flux for $B = 10^{-20.5}$ G is comparable to the 50% confidence upper limit, neither favoring nor excluding this $B$ value, whereas that for $B = 10^{-20}$ G is not constrained by the limit and this $B$ value remains allowed.

We now consider the probability distribution function of the true flux and calculate the probability $P_i$ that it is less than the expected pair-echo flux for the $i$th bin. To combine $P_i$, we use the inverse normal method, a type of meta-analysis. First, we derive the $Z$ value of the normal distribution for the $i$th bin, $Z_i$, which is the percentile (point) of the one-sided $P$ value $P_i$. Note that $Z_i$ is negative if $P_i < 0.5$. Next, we compute the total $Z$ value $Z_{\text{tot}}$ as

$$Z_{\text{tot}} = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} Z_i,$$

where $N$ is the number of the selected bins. Finally, we derive the one-sided $P$ value $P_{\text{tot}}$ of the normal distribution that corresponds to the above $Z_{\text{tot}}$. We can interpret $P_{\text{tot}}$ such that the assumed value of $B$ is excluded at a confidence level of $P_{\text{tot}}$.

Figure 5 shows $Z_{\text{tot}}$ as a function of $B$. For $B \leq 10^{-20.5}$ G, the delay time of the pair echo is determined by angular spreading and becomes independent of $B$. Such weak IGMFs including $B = 0$ is excluded by about $4\sigma$ significance. The significance decreases for larger $B$, and no constraints are obtained for $B \geq 10^{-19.7}$ G. This is a consequence of the lack of any time bins for which the pair-echo flux exceeds the $2\sigma$ Fermi-LAT sensitivity when $B \geq 10^{-19.5}$ G.

Here we have not considered emission components other than the pair echo in the GeV band. In reality, there is likely to be

![Figure 4. Daily Fermi-LAT 2σ sensitivity (dotted), pair-echo light curves for $B = 10^{-20.5}$ G (solid) and $B = 10^{-20}$ G (dashed), and Fermi 50% confidence upper limits (crosses), all at 1–10 GeV.](image)
primary GeV emission from the blazar, and possibly also other types of secondary GeV emission (e.g., Essey et al. 2011). If such components can be reliably accounted for, stronger upper limits on the pair echo and hence stronger lower bounds on the IGMF would be obtainable from the same Fermi data.

5. DISCUSSION AND SUMMARY

Using data from long-term, simultaneous GeV–TeV observations of Mrk 421 by Fermi-LAT and ARGO-YBJ, we have constrained the flux of secondary pair echoes and derived lower bounds on the IGMF strength in the large void region lying between our Galaxy and Mrk 421. This was done by (1) calculating the daily pair-echo flux from the TeV data over 600 days, (2) selecting the dates where the expected pair-echo flux exceeds the Fermi-LAT 2σ sensitivity, (3) computing the probability that an assumed value of the IGMF is excluded by the Fermi-LAT data for each date, and (4) combining these probabilities to derive the total probability using the inverse normal method. Consequently, as long as plasma instabilities are inconsequential, IGMFs weaker than 10^{-20.5} G are excluded by about 4σ for a field coherence length of 1 kpc. For general values of r_{coh}, the derived constraint is \( B \gtrsim 10^{-22} \text{max} \left[ (r_{coh}/350 \text{kpc})^{-1/2}, 1 \right] \text{G} \), where the latter case corresponds to IGMFs that are coherent over the IC cooling length.

Improving on our previous analysis using Mrk 501 (Takahashi et al. 2012), no assumptions are made here concerning the TeV emission during unobserved periods. The obtained constraints are thus more robust than from other studies, particularly those based on limits to the spatially extended halo emission from secondary pairs that inevitably involves very long time delays, often longer than the typical lifetimes of blazars. Although the value of the lower limit obtained here is similar to our previous work, the statistical significance has increased remarkably, from less than 2σ to about 4σ, thanks to the much larger data and improved statistical analysis.

In our study, the errors in the TeV flux, which propagate to the errors in the expected pair-echo flux, have not been considered. However, assuming a Gaussian distribution for the errors, the probability that the true echo flux is larger (or smaller) than the central value is 50%, so the errors in the expected echo flux should cancel out among the data bins to some extent and is unlikely to affect the total P value significantly.

Here we have used the Fermi-LAT data only as daily upper limits to the GeV fluxes. Because the pair-echo flux is strongly dependent on the TeV flux, we can obtain potentially tighter constraints on the IGMF by investigating statistical correlations between the Fermi-LAT data and the ARGO-YBJ data. This will be presented elsewhere in the near future.

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