TIMEx DELAY OF CASCADE RADIATION FOR TeV BLAZARS AND THE MEASUREMENT OF THE INTERGALACTIC MAGNETIC FIELD

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ABSTRACT

Recent claims that the strength $B_{\text{IGMF}}$ of the intergalactic magnetic field (IGMF) is $\gtrsim10^{-18}$ G are based on upper limits to the expected cascade flux in the GeV band produced by blazar TeV photons absorbed by the extragalactic background light. This limit depends on an assumption that the mean blazar TeV flux remains constant on timescales $\gtrsim2(\lambda_{\gamma\gamma}/10^{18}\text{G})^2/(E/10\text{ GeV})^2$ yr for an IGMF coherence length $\approx1$ Mpc, where $E$ is the measured photon energy. Restricting TeV activity of 1ES 0229+200 to $\approx3$–4 years during which the source has been observed leads to a more robust lower limit of $B_{\text{IGMF}} \gtrsim 10^{-18}$ G, which can be larger by an order of magnitude if the intrinsic source flux above $\approx5$–10 TeV from 1ES 0229+200 is strong.

Key words: galaxies; jets – gamma rays; galaxies – radiation mechanisms: non-thermal

1. INTRODUCTION

The measurement of the intergalactic magnetic field (IGMF) gives information about processes operating in the early universe that are imprinted on the large-scale structure of the universe (see Neronov & Semikoz 2009). Faraday rotation measurements of the radio emission of quasars, patterns in the arrival directions of UHECRs toward the supergalactic plane and Cen A, and theoretical arguments from Cosmic Background Explorer data (Barrow et al. 1997) indicate that $B_{\text{IGMF}} \ll 10^{-8}$ G, but no direct measurements or lower limits of the IGMF in the voids have been firmly established. Gamma-ray astronomy has a method to measure the IGMF through magnetic field-induced delays (Plaga 1995), pair halos from sources of TeV photons directed away from our line of sight (Aharonian et al. 1994), and halos around (Ellyiv et al. 2009) and cascade-radiation spectra of (Dai et al. 2002; D’Avezac et al. 2007; Murase et al. 2008; Neronov & Vovk 2010; Tavecchio et al. 2010a, 2011) point sources of high-energy $\gamma$ rays.

In the latter approach, TeV photons from cosmic $\gamma$-ray sources interact with photons of the extragalactic background light (EBL) to produce $e^−e^+$ pairs. If the pairs are not significantly deflected by the IGMF, cosmic microwave background (CMB) photons, which dominate the radiation energy density in intergalactic space, are Compton scattered in the original direction of the pairs. Deflection out of the TeV beam depends on the jet opening angle $\theta_j$. By comparing blazar TeV fluxes with upper limits on the GeV radiation flux measurements with the Fermi Gamma-ray Space Telescope, several claims (see Table 1) have been made that lower limits on the IGMF have been measured (Neronov & Vovk 2010; Tavecchio et al. 2010a, 2011; Dolag et al. 2011). These limits, which depend on the assumed opening angle $\theta_j$ of the TeV photon source, are summarized in Table 1 for the TeV blazar 1ES 0229+200 at redshift $z = 0.1396$. Under the assumption of persistent TeV emission over long timescales, these studies find that $B_{\text{IGMF}} \gtrsim 10^{-18}$ G for magnetic coherence (or correlation) lengths $\lambda_{\text{coh}} \sim 1$ Mpc when $\theta_j \approx 0.1$.

Implicit in all these studies is that the TeV blazars used to infer the IGMF emit constant flux over a long period of time. Because blazars are highly variable, a more defensible limit is obtained (lacking other ways to infer a blazar’s TeV activity lifetime) by assuming that the TeV emission is emitted only over the past few years during which it has been monitored. A simple semi-analytic approach is used to derive minimum values, for comparison with numerical models (Dolag et al. 2011; Taylor et al. 2011).

2. TIME DELAY AND DEFLECTION ANGLE OF EMISSION FROM FIRST-GENERATION PAIRS

Consider a source and observer separated by distance $d$, as shown in Figure 1. Photons with dimensionless energy $\epsilon_1 = h\nu_1/m_e c^2 \approx 2 \times 10^6 E_1 (\text{TeV})$ emitted at angle $\theta_1$ to the line of sight between the source and observer travel a mean distance $l_{\gamma\gamma} = l_{\gamma\gamma}(\epsilon_1, z)$ before converting into an electron–positron pair via $\gamma\gamma$ absorption with photons of the EBL. The pairs cool by scattering CMB photons to $E_{\text{GeV}}$ GeV energies, which are detected at an angle $\theta$ to the line of sight to the source when the secondary electrons and positrons (hereafter referred to as electrons) are deflected by an angle $\theta_d$. The GeV emission, to be detected, must be within the energy-dependent Fermi Large Area Telescope (LAT) point-spread function (psf) angle $\theta_{\text{psf}}(E_{\text{GeV}})$. The system is treated in the low-redshift limit (cf. Neronov & Semikoz 2009).

The time delay $\Delta t$ between the reception of photons directed toward the observer and those formed by the process described above is given by

$$c\Delta t = \frac{d \sin(\theta_{\text{def}} - \theta)}{\sin \theta_{\text{def}}} = \frac{\lambda_{\gamma\gamma}(1 - \cos \theta_{\text{def}}) - d(1 - \cos \theta)}{2c \theta_{\text{def}}^2},$$

where $d = d \sin \theta_1/\sin \theta_{\text{def}}$ and $\lambda_{\gamma\gamma} = d \sin \theta_1/\sin \theta_{\text{def}}$. In the limit of small observing and deflection angles, Equation (1) implies

$$\Delta t \approx \frac{\lambda_{\gamma\gamma}}{2c} \theta_{\text{def}}^2.$$
we write $\lambda_{\gamma\gamma} = 100\lambda_{100}$, though we use the accurate energy dependence of $\lambda_{\gamma\gamma}(E_{\gamma\gamma})$ in the numerical calculations. The importance of pair cascade radiation with angular extent broader than the Fermi LAT psf depends on the value of

$$\frac{\lambda_{\gamma\gamma}}{\lambda_{psf}} \approx \frac{d}{\theta_{psf}(E_{\gamma\gamma})} \frac{\tau_{\gamma\gamma}(E_{\gamma\gamma})}{\theta_{psf}(E_{\gamma\gamma})},$$

(5)

where $\lambda_{psf}$ is the effective distance a primary photon would have to travel to make a GeV photon detected at the edge of the Fermi psf given the parameters of the intergalactic medium. The value of $\theta_{psf}(E_{\gamma\gamma})$, taken here as the 95% Fermi LAT confinement angle, is from the Fermi LAT instrument performance page\footnote{http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm} (see also Rando 2009; Taylor et al. 2011). For the EBL model of Finke et al. (2010), the cascade emission can be treated as a point source when $B_{-15} < 0.05 E_{\gamma\gamma}^{0.6}$ for $0.2 \lesssim E_{\gamma\gamma} \lesssim 20$.

For a source at distance $d = d_{\text{Gpc}}$ Gpc, with $d_{\text{Gpc}} \sim 1$ corresponding to $z \sim 0.2$, the time delay for emission observed at angle

$$\theta \equiv 0.01 \frac{\lambda_{100}}{d_{\text{Gpc}}} \left( \frac{B_{-15} w}{E/10 \text{ GeV}} \right),$$

(6)

from the line of sight is given from Equation (2) by

$$\Delta t(\text{yr}) \approx 2 \times 10^6 \lambda_{100} \left( \frac{B_{-15} w}{E/10 \text{ GeV}} \right)^2.$$

(7)

Short delay times are restricted to conditions of small $B_{\text{IGMF}}$ and large $E$ where, as just seen, extended pair halo emission can be neglected.

Equation (7) shows that small time delays are implied when $\lambda_{\gamma\gamma}$ is small and $\lambda_{psf}/\lambda_{\gamma\gamma} > 1$. When $\lambda_{\gamma\gamma} \ll \lambda_T$, an additional delay $\approx \lambda_T^2 \sqrt{\theta_{psf}^3 / c}$ arises during the time that the electrons are losing energy and being deflected by the IGMF (Murase et al. 2008; Ichiki et al. 2008; Razzaga et al. 2004). Such small values of $\lambda_{\gamma\gamma} \sim 1$ Mpc are only relevant at low redshifts for $\gtrsim 100$ TeV photons that pair-produce within $\sim 1$ Mpc of their source, where the magnetic field may not be representative of the dominant volume of the voids.

### Table 1

| Source 1ES 0229+200 | $\theta_0$ (rad) | $B_{\text{IGMF}}$ (G) |
|---------------------|-----------------|---------------------|
| Dolag et al. (2011) | $\pi$            | $3 \times 10^{-16}$ |
| Tavecchio et al.    | 0.1             | $5 \times 10^{-15}$ |
| Neronov & Vovk      | 0.03            | $2 \times 10^{-15}$ |
| Dolag et al. (2011) | 0.1             | $5 \times 10^{-15}$ |

provided that the photon is detected at an angle

$$\theta = \frac{\lambda_{\gamma\gamma}(E_{\gamma\gamma}) \theta_{psf}(E_{\gamma\gamma})}{d} < \frac{\theta_{psf}(E_{\gamma\gamma})}{d_{\text{Gpc}}}$$

(3)

to the source. Note that the deflection angle depends on either the primary photon energy $E_{\gamma\gamma}$ or Compton-scattered photon energy $E_{\gamma\gamma}$, since they are related by $E_{\gamma\gamma} \approx E_{\gamma\gamma}$, as we now show.

The average CMB photon energy at low redshift is $E_0 \approx 1.24 \times 10^{-3}$ in $m_e c^2$ units, so that the mean Thomson-scattered photon energy $\epsilon_T \approx (4/3) \epsilon_0 y^2$, where $y \equiv E_{\gamma\gamma}/(2 m_e c^2)$ implies $y_0 \approx 0.98 E_{\gamma\gamma}$. Thus, an electron with Lorentz factor $\gamma$ scatters CMB radiation to photon energy $E$ when $y_0 \approx E_{\gamma\gamma} \approx 1.1 \sqrt{E_{\gamma\gamma}}$. The characteristic length scale for energy losses due to Thomson scattering is $\lambda_T = 3 m_e c^2 / 4 \pi \gamma^2 \epsilon_T$ (CMB)$\gamma$ = (0.75/1000) Mpc, where $u_{\gamma\gamma} \approx 4 \times 10^{-13}$ erg cm$^{-3}$ is the CMB energy density at low redshifts. While losing energy, the electron is deflected by an angle $\theta_0 \approx \lambda_T / r_{\text{Larmor}}$ in a uniform magnetic field of strength $B_{\text{IGMF}} = 10^{-15} B_{-15}$ G oriented perpendicular to the direction of motion of the electron, where the Larmor radius $r_{\text{Larmor}} = m_e c^2 \epsilon_T / e B \approx 0.55 (y_0 / B_{-15})$ Mpc. Thus, the deflection angle for an electron losing energy by scattering CMB photons to energy $E$ in a uniform field is $\theta_0 = \lambda_T / r_{\text{Larmor}} \approx 1.1 B_{-15} / E_{\gamma\gamma}$. Introducing a coherence length $\lambda_{\text{coh}}$ that characterizes the typical distance over which the magnetic field direction changes by $\approx \pi/2$, then the deflection angle

$$\theta_{\text{diff}} = w \theta_0,$$

with $w = \left\{ \begin{array}{ll} \lambda_{\text{coh}} / \lambda_T & \text{if } \lambda_T < \lambda_{\text{coh}}; \\ \lambda_T / \lambda_{\text{coh}} & \text{if } \lambda_T > \lambda_{\text{coh}}. \end{array} \right.$$

(4)

For 1ES 0229+200, TeV radiation has been detected to energies $E \lesssim 12$ TeV (Aharonian et al. 2007), with an approximate 15% error in the energy measurement. An uncertainty in the analytic treatment is that the mean free path $\lambda_{\gamma\gamma}(E_{\gamma\gamma})$ varies by a factor of $\approx 2$ between $\gamma \rightarrow 0$ and $\gamma = 0.14$, and between different EBL models. For instance, the EBL model of Finke et al. (2010) gives $\lambda_{\gamma\gamma}(E) \approx 200$ Mpc, 125 Mpc, and 70 Mpc at $E = 1, 3,$ and 10 TeV, respectively, and a low EBL model based on galaxy counts (Kneiske $\&$ Dole 2010) gives $\lambda_{\gamma\gamma}(E) \approx 280$ Mpc, 150 Mpc, and 85 Mpc, respectively. For analytic estimates,
v9r15p5).\(^8\) The P6_V3_DIFFUSE set of instrument response functions was used. Photons were selected in a circular region of interest (ROI) 10° in radius, centered at the position of 1ES 0229+200. The isotropic background, including the sum of residual instrumental background and extragalactic diffuse γ-ray background, was modeled by fitting this component at high galactic latitude (isotropic_\text{iem}_v02.fit, available from the FSSC Web site). The Galactic diffuse emission model version “gll_iem_v02.fit” was used in the analysis. The profile likelihood method (Rolke et al. 2005) was used to extract 95% confidence level upper limits at the location of 1ES 0229+200 assuming a power-law energy distribution with photon index = 2, all 1FGL point sources lying within the ROI being modeled with power-law distributions. The upper limits shown in Figure 2 are obtained in the energy bins 0.1–1 GeV, 1–3 GeV, 3–10 GeV, 1–10 GeV, and 10–100 GeV.

4. MODEL FOR CASCADE RADIATION

The limits on the IGMF can be established by employing a simple semi-analytic model for the cascade-radiation spectrum. Using the notation that \( f_e = \nu F_\nu \) at dimensionless photon energy \( \epsilon \), and that each photon is attenuated into a pair with each electron taking one-half the original photon’s energy, then a straightforward derivation gives

\[
f_e = \frac{3}{2} \left( \frac{\epsilon}{\epsilon_0} \right)^2 \int_{\epsilon_0}^{\epsilon} \left( \frac{\nu}{\nu_0} \right)^{-\delta - 4} \left( 1 - \frac{\epsilon}{4\nu^2} \right) dy \left[ \exp\left( \frac{\nu}{\nu_0} \frac{y(z)}{\epsilon} \right) - 1 \right]
\]

where \( y_1 = \epsilon / 2 \). The interior integrand represents the fraction of deabsorbed source photon flux converted to pairs and the exterior integral represents the Compton-scattered spectrum from cooled electrons (cf. Razzaque et al. 2004; Murase et al. 2008; Ichiki et al. 2008). The opacity due to EBL attenuation for photons with measured dimensionless energy \( \epsilon \) from a source at redshift \( z \ll 1 \) is \( \tau_{\gamma\gamma}(\epsilon, z) \) and depends on the EBL model.

Equation (8) employs the isotropic Thomson kernel, with the CMB radiation approximated as a monochromatic radiation field, but the results in Figure 2 are also integrated over the energy distribution of the blackbody radiation field. The use of the Klein–Nishina kernel makes negligible difference for photons with energy \( \gtrsim 50 \text{ TeV} \). In the three terms in the lower limit of the exterior integration, the first gives the kinematic minimum electron Lorentz factor to scatter a CMB photon to energy \( \epsilon_0 \). The second is the value of the deflection Lorentz factor \( \gamma_{\text{def}} \) obtained by equating the Thomson cooling time and the timescale \( \theta_{\text{BL}} c / \epsilon \) when the electron is deflected outside the photon beam of opening angle \( \theta \). The third limit, \( \gamma'(\Delta\gamma) \), represents the Lorentz factor to which electrons have cooled after the blazar engine has been operating for time \( \Delta\gamma \) and follows from Equation (2) by solving \( \Delta\gamma(\gamma\gamma) < \Delta\gamma_{\text{eng}} \) for \( \gamma_{\text{eng}} = \gamma'(\Delta\gamma) \). Here we approximate \( \lambda_{\gamma\gamma}(E_{\text{TeV}}) \approx d / \tau_{\gamma\gamma}(E_{\text{TeV}}) \) Mpc, using a fit to the Finke et al. (2010) EBL model for 1ES 0229+200. A calculation with \( \lambda_{\gamma\gamma}(E_{\text{TeV}}) \approx d / (2\tau_{\gamma\gamma}(E_{\text{TeV}})) \) Mpc gives similar results. Only the first generation of cascade emission attenuated by the factor \( \exp[-\tau_{\gamma\gamma}(\epsilon_1, z)] \) is shown here.

Results of calculations using this simplified analytic model are shown in Figure 2. Figure 2(a) is a calculation where the blazar engine operates for indefinitely long times, with

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\(^8\) http://fermi.gsfc.nasa.gov/ssc/
the reduction of cascade flux due to deflection away from the beam for a jet and the detection of a plateau flux of isotropized radiation determined by the jet opening angle $\theta_j = 0.1$ (Tavecchio et al. 2010a). The source spectrum is described by a superexponential cutoff power law $v F_v \propto E^{4/5} \exp[-(E/5\text{TeV})^2]$ in Figures 2(a) and (b), and by an exponential cutoff power law $v F_v \propto E^{4/5} \exp[-E/10\text{TeV}]$ in Figure 2(c). In agreement with previous results (Neronov & Vovk 2010; Tavecchio et al. 2010a, 2011; Dolag et al. 2011), a value of $B_{\text{IGMF}} \gtrsim 3 \times 10^{-16} \text{G}$ is implied in order to reduce the GeV flux below the Fermi upper limit. From the calculations, we also find that under the assumption of persistent TeV blazar emission, halo emission becomes increasingly dominant for large jet opening angles. Detection of halos around active galactic nuclei, as claimed by Ando & Kusenko (2010; cf. Neronov et al. 2011), would then favor detection in sources with large opening angle, long-lived TeV engines. Also under the persistent emission hypothesis, a maximum jet opening angle $\theta_j \lesssim 0.4$ is implied in order that the isotropized radiation does not violate the Fermi LAT upper limits.

The effects of $B_{\text{IGMF}}$ on the received spectrum of reprocessed TeV radiation when the blazar engine is assumed to emit a constant TeV flux over an engine time $\Delta_{\text{eng}} \equiv 3 \text{ yr}$ are shown in Figures 1(a) and (b). These calculations show that $B_{\text{IGMF}} \gtrsim 3 \times 10^{-19} \text{G}$ for the case where the assumed source spectrum sharply cuts off above 5 TeV. Uncertainties in the analytic model, including the strong sensitivity of the cascade spectrum on $\gamma_{\text{eng}}$, relax our conclusions to an analytic, order-of-magnitude minimum IGMF of $B_{\text{IGMF}} \gtrsim 10^{-18} \text{G}$ for $\Delta_{\text{eng}} \equiv 3 \text{ yr}$. Figure 2(c) shows that the minimum magnetic field also depends sensitively on the characterization of the high-energy spectral flux, which can then quickly cascade into the 10–100 GeV band and violate a Fermi upper limit (or marginal detection; see Orr et al. 2011). By assuming source spectra with larger fluxes above $\approx 5–10 \text{ TeV}$, Dolag et al. (2011) and Taylor et al. (2011) derive larger values for the minimum $B_{\text{IGMF}}$, but not more than a factor of a few above the analytic results when difference in activity times and primary source fluxes are considered.

5. DISCUSSION AND SUMMARY

Previous GeV/TeV inferences of the strength of the IGMF make an assumption that the mean blazar TeV flux over millions of years remains similar to values observed over the last few years. Our knowledge of the blazar engine is not yet so good as to have high confidence in this assumption, though some models for slowly varying TeV flux from TeV blazars can be noted. For example, a slow cooling rate of the electrons that make the TeV photons could imply a slowly varying $\gamma$-ray flux even if the blazar engine is very active. For electrons scattering photons to TeV energies, the synchrotron cooling time for the observer is $t_{\text{syn}} \approx (1 + z) 36 \sigma m_e c / (\delta B \sigma T B^2 \gamma^3) \approx 50 / (E \text{ TeV}) \text{ yr}$, using the fitting parameters of Tavecchio et al. (2010b) for 1ES 0229+200 (break Lorentz factor $\gamma_b = 5 \times 10^6$, emission region magnetic field $B' = 5 \times 10^{-4} \text{G}$, and Doppler factor $\delta_B = 40$). Relativistic electrons in an extended jet that Compton scatter photons of the CMB could also make slowly varying TeV radiation in sources like 1ES 0229+200 or 1ES 1101–232 (Böttcher et al. 2008). In this model, relativistic electrons lose energy on timescales of $\approx 750 / [\Gamma (10)^2] \text{yr}$. These models do not, however, provide good reasons to expect TeV blazars to produce steady flux for thousands of millions of years.

A more reliable limit is obtained from direct measurements of TeV fluxes. For the handful of observations of 1ES 0229+200 over 3–4 years of observing (Aharonian et al. 2007; Perkins 2010), no TeV flux variations have been reported. Using such timescales leads to a limit of $B_{\text{IGMF}} (\text{G}) \gtrsim 10^{-18} (E/10 \text{GeV})/\Delta t/3 \text{yr}/\sqrt{\lambda_{\text{coh}}}$, assuming that $\lambda_{\text{coh}} \approx 1 \text{ Mpc}$. By assuming strong intrinsic $\gtrsim 10 \text{ TeV}$ emission from 1ES 0229+200 (which is not observed because of EBL attenuation), Fermi LAT flux upper limits at $\approx 100 \text{ GeV}$ can be violated, leading to larger limiting values of $B_{\text{IGMF}} (\text{G}) \gtrsim 5 \times 10^{-18} \text{G}$. Evidence for a strong primary flux at $\gtrsim 10 \text{ TeV}$ comes from detection of a shoulder feature at $\approx 1 \text{ TeV}$, as found in the numerical calculations (Dolag et al. 2011) and analytical results (Figure 2(c)), and suggested by the joint VERITAS/HESS data. Note that our calculations assume negligible contribution from cascades induced by photopair interactions by $\gtrsim 10^{-18} \text{eV} \text{ cosmic rays}$ (Essey et al. 2010). More frequent, sensitive, and broadband GeV–TeV observations of 1ES 0229+200 can test whether the average TeV flux corresponds to the flux that has been historically measured or is unusual.

Evidence for long-lived TeV radiation can be identified in pair halos (Aharonian et al. 1994) from misaligned blazar candidates such as Cen A or M87. Searches for pair echoes from GRBs, which are sensitive at $\ll 10^{-2}/\lambda_{\text{coh}}$ (Mpc) G (Takahashi et al. 2008), would test our claim that $B_{\text{IGMF}} \gtrsim 10^{-18} \text{G}$. A large field-of-view detector like the High Altitude Water Cherenkov telescope (Goodman 2010), or systematic monitoring campaigns of blazars such as 1ES 0229+200, 1ES 1101–232 ($z = 0.186$, 1ES 0347–121 ($z = 0.185$) or other bright, moderate redshift BL Lac objects with the present generation of air Cherenkov telescopes or an advanced Cherenkov telescope array, will give better information about the duty cycle of TeV blazars and provide more secure constraints on the value of the IGMF.

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