

Extreme TeV Blazars and Lower Limits on Intergalactic Magnetic Fields

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The intergalactic magnetic field (IGMF) in cosmic voids can be indirectly probed through its effect on electromagnetic cascades initiated by a source of TeV gamma rays, such as blazars, a subclass of active galactic nuclei. Blazars that are sufficiently luminous at TeV energies, “extreme TeV blazars”, can produce detectable levels of secondary radiation from inverse Compton scattering of the electrons in the cascade, provided that the IGMF is not too large. We review recent work in the literature which utilizes this idea to derive constraints on the IGMF for three TeV-detected blazars-1ES 0229+200, 1ES 1218+304, and RGB J0710+591, and we also investigate four other hard-spectrum TeV blazars in the same framework. Through a recently developed detailed 3D particle tracking Monte Carlo simulation code, incorporating all major effects of QED and cosmological expansion, we research effects of major uncertainties such as the spectral properties of the source, uncertainty in the intensity of the UV - far IR extragalactic background light (EBL), under-sampled Very High Energy (VHE; energy ≥ 100 GeV) coverage, past history of gamma-ray emission, source vs. observer geometry, and jet AGN Doppler factor. The implications of these effects on the recently reported lower limits of the IGMF are thoroughly examined to conclude that presently available data are compatible with a zero IGMF hypothesis.

1. Introduction

It is well known that astrophysical magnetic fields are ubiquitous in galaxies and galaxy clusters on the order of a micro Gauss (see e.g. Grasso and Rubinstein [2001], Widrow [2002]). Furthermore, there is increasing theoretical evidence based on numerical simulations of structure formation that nano Gauss order fields permeate filaments of the large scale structure (see e.g. Ryu et al. [2008]). However, at present there has been no detection of the intergalactic magnetic field (IGMF) presumed to exist in the Cosmic Void regions of the large scale structure. The detection of the IGMF could provide important insights for solving outstanding problems of its origin and role in both the cosmology and astrophysics of structure formation [Grasso and Rubinstein 2001, Widrow 2002, Zweibel 2006, Kronberg 1994].

Until recently, only upper limits on B_{IGMF} have been established, on the order of $B_{IGMF} \sim 10^{-9}$ Gauss, at a correlation length of 1 Mpc, and this limit weakens as the correlation length (λ_c) decreases as $\sim \lambda_c^{-1/2}$ [Neronov and Semikoz 2009]. However, a more sensitive technique has emerged during the past few years which may become a tool for the measurement of IGMF characteristics. This technique relies on observations of blazars, in the energy range from 100 MeV to greater than 10 TeV and is described by several authors [Neronov and Semikoz 2006, Eungwanichayapant and Aharonian 2009, Dolag et al. 2009, Elyiv et al. 2009]. Briefly, TeV-scale gamma rays from the blazar interact with the UV to far-IR extragalactic background light (EBL), producing electron-positron pairs, which then undergo inverse Compton (IC) scattering on the CMB photons, producing secondary gamma rays of a lower energy than the primary. Because the pairs’ trajectories depend on the interactions with the magnetic field, comparing the GeV-scale secondary gamma ray radiation with exist-

ing data can be used to characterize properties of the IGMF.

In the past few years, a number of studies [Neronov and Vovk 2010, Tavecchio et al. 2010, Dermer et al. 2011, Huan et al. 2011, Dolag et al. 2011, Taylor et al. 2011] have demonstrated that a lower limit on the IGMF strength can in principle be derived by requiring that the secondary gamma ray GeV radiation which would be produced at a given B_{IGMF} not exceed the measured value. A consensus has begun to emerge that a minimum value of $B_{IGMF} \approx 10^{-17} - 10^{-18}$ Gauss is required to explain the observations. With a newly developed 3-dimensional Monte Carlo code combined with a detailed and general statistical analysis method, the purpose of these proceedings is to show that the current observational data is consistent with the $B_{IGMF} = 0$ hypothesis, when the systematic and statistical uncertainties are accounted for.

2. Monte Carlo Simulations

In order to explore in detail the potentially observable effects of cascading in the voids of the large scale structure, we have developed a fully 3-dimensional Monte Carlo code, which propagates individual particles of the cascade in a cosmologically expanding Universe and accounts for the QED interactions with the EBL and CMB without simplifications.

The spectral energy density of the EBL from the UV to the far-IR is not precisely known, and therefore we choose to model it with specific SEDs close to the energy density of the recent EBL model of Domínguez et al. [2011]. The magnetic field is described as a system of cubic cells with an edge length set to 1 Mpc, with equal field amplitudes in each cell, but randomly oriented in direction.

The gamma ray source model employed is based on

leading theoretical speculations about the nature of the TeV blazar source (see e.g. Urry and Padovani [1995]). In the reference frame of the blazar jet, GeV - TeV photons are distributed isotropically with a broken power law spectrum of index α for the higher energy component and γ for the lower energy component. Once this distribution is boosted into the reference frame of the host galaxy with a doppler boost factor of $\Gamma = (1 - \beta^2)^{-1/2}$, the observed differential flux energy density (dFED) can be parameterized as

$$\epsilon \frac{dF}{d\epsilon} = F_0 \delta^2 \begin{cases} \left(\frac{\epsilon}{\epsilon_B \delta}\right)^{-\gamma+1} \exp\left(\frac{-\epsilon}{\epsilon_c}\right) & \frac{\epsilon}{\epsilon_B \delta} < 1 \\ \left(\frac{\epsilon}{\epsilon_B \delta}\right)^{-\alpha+1} \exp\left(\frac{-\epsilon}{\epsilon_c}\right) & \frac{\epsilon}{\epsilon_B \delta} > 1 \end{cases}. \quad (1)$$

where ϵ is the photon energy in the reference frame of the host galaxy, $\delta = [\Gamma(1 - \beta \cos \theta_v)]^{-1}$, θ_v is the viewing angle from the blazar jet axis to the line of sight of the observer, F_0 is a flux normalization factor, ϵ_c is the exponential cutoff energy, and ϵ_B is the spectral break energy. This six parameter γ -ray source spectrum is given at the redshift of the host galaxy and is necessary and sufficient to satisfy observational data of TeV blazars in both the HE (*Fermi*-LAT) and VHE (IACT) regimes, and it is more general than previous studies which only considered single intrinsic power law models for the primary gamma ray emission, over the energy range spanning more than five orders of magnitude from ≈ 100 MeV to > 10 TeV.

3. Testing the $B_{IGMF} = 0$ hypothesis

The most comprehensive work yet on constraining the IGMF was done by Taylor et al. [2011] (hereafter referred to as TVN11), in which three sources were found (RGB J0710+591, 1ES 1218+304, and 1ES 0229+200) whose combined quasi-simultaneous IACT and *Fermi*-LAT dFED are not compatible with the $B_{IGMF} = 0$ hypothesis at greater than 95% confidence level. It was suggested that $B_{IGMF} \geq 10^{-17}$ G is required to explain observations.

With the newly developed simulation and analysis code, we re-examined the conclusion of a lower limit on B_{IGMF} . The spectral model of Eq 1 was fit to the same IACT data as used in TVN11, but with about one more year of *Fermi* data. A large range of parameter space of the model was scanned over (α , ϵ_c , F_0 , γ , ϵ_B), while several parameters were left fixed, including 1) a fixed source-observer geometry of $\Gamma = 10$ and $\theta_v = 0^\circ$, 2) the EBL model with an SED very close to Domínguez et al. [2011], 3) the duty cycle of the TeV emission, and 4) assuming no structures with an enhanced magnitude of magnetic field (for ex: galaxy clusters, filaments, etc.) between the source and observer. For each model, a χ^2 fit to the combined IACT/*Fermi* data was performed, and

also the corresponding confidence level for rejecting the $B_{IGMF} = 0$ hypothesis. (For more details on this procedure, as well as the chosen data sets, please see Arlen et al. [2012]). The best fitting models for each source are shown in Fig 1. The first two sources, RGB J0710+591 and 1ES 1218+304 (Fig 1 a and b) were found to be incompatible with the $B_{IGMF} = 0$ hypothesis at $< 90\%$, which does *not corroborate the conclusion of TVN11 that the $B_{IGMF} = 0$ hypothesis is rejected for these sources.* It was found that a combination three factors were the primary reasons for this discrepancy, which are the following: 1) the updated Pass 7 *Fermi*-LAT data used in the present work, 2) the more general description of the broken-power law source model in the analysis of the data, and 3) the more robust statistical analysis which used information about the cascade flux to define the spectral index in each bin as an input to the Fermi likelihood spectral analysis.

It is confirmed that the data for 1ES 0229+200 are incompatible with the $B_{IGMF} = 0$ hypothesis at $> 99\%$ confidence level, with the standard assumptions of 1) - 4) (listed in the previous paragraph). Since only this single source was found to be in conflict with a non-zero IGMF, each of these standard assumptions were varied to within their uncertainty limits to research all the possible ways in which the non-zero IGMF requirement can fail. For example, the duty cycle assumption was varied, because the 3 year time-averaged *Fermi*-LAT spectrum is combined in the spectral model fits with the VHE spectrum which is averaged over a much shorter time period. Thus, it is necessary to make an assumption regarding the stability of the pointed VHE observations (duty cycle). To investigate the effect of a reduced duty cycle, the spectrum of this source was modified at the highest 5 energy points to half an order of magnitude of their reported values. It was found that the VHE-HE data set combined in this way does not rule out the $B_{IGMF} = 0$ hypothesis to more than 95 % confidence level. Therefore, if the true 3-year time-averaged spectrum is over-estimated by about 50 %, then compatibility with the $B_{IGMF} = 0$ hypothesis would be achieved. A similar compatibility could be achieved if the location of the source within a filament is separated by at least a few hundred Mpc from the nearest Cosmic Void. The enhanced magnetic field within a filament could potentially isotropize the electrons before IC scattering occurs along the line of sight to the observer and could also explain the observations without invoking a non-zero IGMF.

Alternatively, the energy density of the EBL in the near IR band can be reduced to the lower limits derived from galaxy counts data to avoid incompatibility with the zero IGMF assumption. This latter case of EBL uncertainty has also been investigated recently [Vovk et al. 2012] to conclude that this data provides joint constraints on the IGMF and EBL in which the

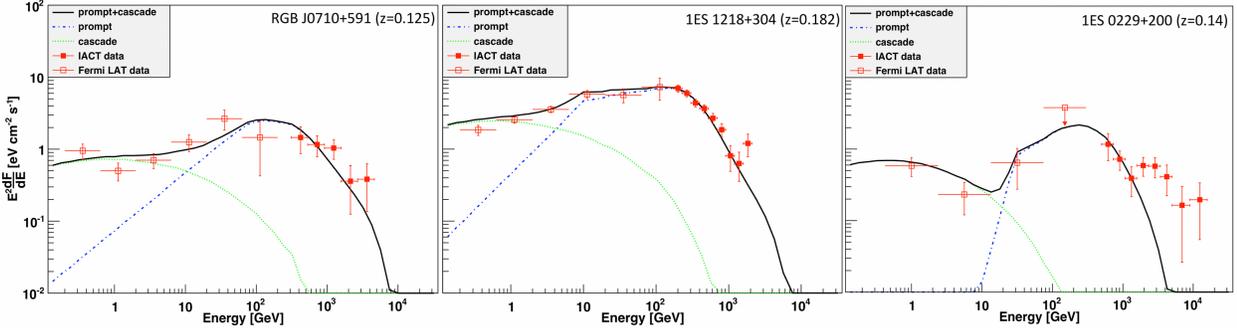


Figure 1: Best fit models for (a) (left) source RGB J0710+591 where $\alpha = 1.8$, $\epsilon_C = 3.16$ TeV, which is inconsistent with the $B_{IGMF} = 0$ hypothesis at $< 90\%$ (b) (middle) source 1ES 1218+304 where $\alpha = 1.8$, and $\epsilon_C = 3.16$ which is inconsistent with the $B_{IGMF} = 0$ hypothesis at $< 80\%$ (c) (right) source 1ES 0229+200 where $\alpha = 1.3$, $\epsilon_C = 1$ TeV, which is inconsistent with the $B_{IGMF} = 0$ hypothesis at $> 99\%$.

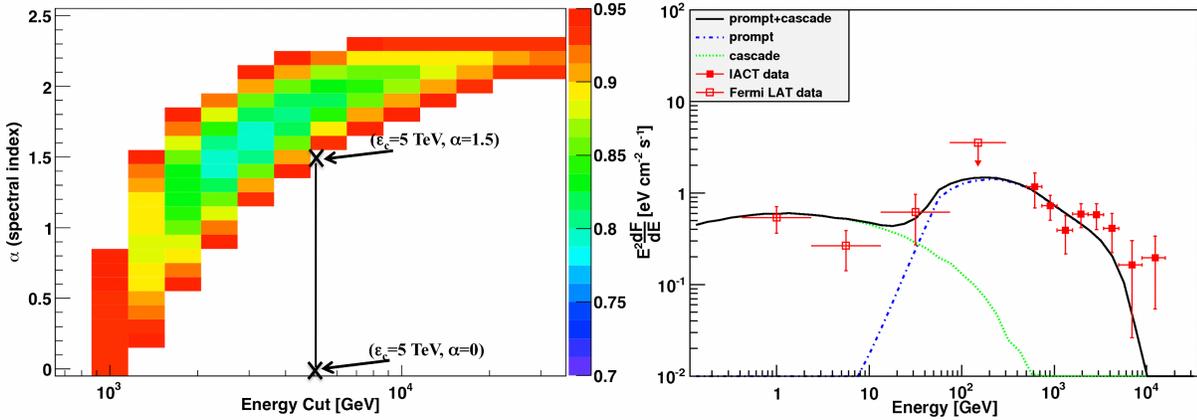


Figure 2: (a) (left) Confidence level for the simulated source models for 1ES 0229+200 obtained under the assumption of a low EBL Model close to the lower limits due to galaxy counts. The black line terminated with crosses represents the range of models analyzed in Vovk et al. [2012]. (b) (right) dFED of 1ES 0229+200 for the best fitting model at $\alpha = 1.6$, $\epsilon_c = 3.16$ TeV.

zero field is in the exclusion region. Figure 2 illustrates our finding that this conclusion is the result of a limited exploration of the parameter space of uncertainties in the intrinsic properties of the source. Therefore, for EBL models which are very low in the near-IR energy density but still allowable by the currently established lower limits, the data of 1ES 0229+200 can be reconciled with a zero magnetic field ($B_{IGMF} = 0$).

4. Discussion

We have investigated the HE–VHE energy spectrum of several extreme TeV blazars for which radiation in the HE band may be dominated by the secondary photons produced through cascading in the voids along the line of sight. These sources are characterized by their observed hard spectra in the VHE band accompanied by redshifts of order ≈ 0.1 suggesting a very large energy output into pair production and subsequent cascading. For these sources, obser-

vations in the HE band can therefore limit the flux of secondary photons and establish a lower bound on the IGMF. This strategy has been utilized in several publications [Neronov and Vovk 2010, Tavecchio et al. 2010, Dermer et al. 2011, Huan et al. 2011, Dolag et al. 2011, Taylor et al. 2011] to suggest $B_{IGMF} \leq 10^{-17} - 10^{-18}$ G in the local cascading environment. In contrast to these studies, we systematically investigated effects of a wide range of uncertainties using detailed 3D Monte Carlo simulations to conclude that the $B_{IGMF} = 0$ hypothesis remains compatible with current observations.

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References

- D. Grasso and H. R. Rubinstein, *Phys. Rep.* **348**, 163 (2001), arXiv:astro-ph/0009061.
- L. M. Widrow, *Reviews of Modern Physics* **74**, 775 (2002), arXiv:astro-ph/0207240.
- D. Ryu, H. Kang, J. Cho, and S. Das, *Science* **320**, 909 (2008), 0805.2466.
- E. G. Zweibel, *Astronomische Nachrichten* **327**, 505 (2006).
- P. P. Kronberg, *Nature* **370**, 179 (1994).
- A. Neronov and D. V. Semikoz, *Phys. Rev. D* **80**, 123012 (2009), 0910.1920.
- A. Neronov and D. V. Semikoz, *ArXiv Astrophysics e-prints* (2006), arXiv:astro-ph/0604607.
- A. Eungwanichayapant and F. Aharonian, *International Journal of Modern Physics D* **18**, 911 (2009), 0907.2971.
- K. Dolag, M. Kachelrieß, S. Ostapchenko, and R. Tomàs, *ApJ* **703**, 1078 (2009), 0903.2842.
- A. Elyiv, A. Neronov, and D. V. Semikoz, *Phys. Rev. D* **80**, 023010 (2009), 0903.3649.
- A. Neronov and I. Vovk, *Science* **328**, 73 (2010), 1006.3504.
- F. Tavecchio, G. Ghisellini, L. Foschini, G. Bonnoli, G. Ghirlanda, and P. Coppi, *MNRAS* **406**, L70 (2010), 1004.1329.
- C. D. Dermer, M. Cavadini, S. Razzaque, J. D. Finke, J. Chiang, and B. Lott, *ApJ* **733**, L21 (2011), 1011.6660.
- H. Huan, T. Weisgarber, T. Arlen, and S. P. Wakely, *ApJ* **735**, L28+ (2011), 1106.1218.
- K. Dolag, M. Kachelriess, S. Ostapchenko, and R. Tomàs, *ApJ* **727**, L4+ (2011), 1009.1782.
- A. M. Taylor, I. Vovk, and A. Neronov, *A&A* **529**, A144 (2011), 1101.0932.
- A. Domínguez, J. R. Primack, D. J. Rosario, F. Prada, R. C. Gilmore, S. M. Faber, D. C. Koo, R. S. Somerville, M. A. Pérez-Torres, P. Pérez-González, et al., *MNRAS* **410**, 2556 (2011), 1007.1459.
- C. M. Urry and P. Padovani, *PASP* **107**, 803 (1995), arXiv:astro-ph/9506063.
- T. C. Arlen, V. V. Vassiliev, T. Weisgarber, S. P. Wakely, and S. Yusef Shafi, *ArXiv e-prints* (2012), 1210.2802.
- I. Vovk, A. M. Taylor, D. Semikoz, and A. Neronov, *ApJ* **747**, L14 (2012), 1112.2534.