Probing the intergalactic magnetic field through observations of high-energy gamma rays produced by electromagnetic cascades

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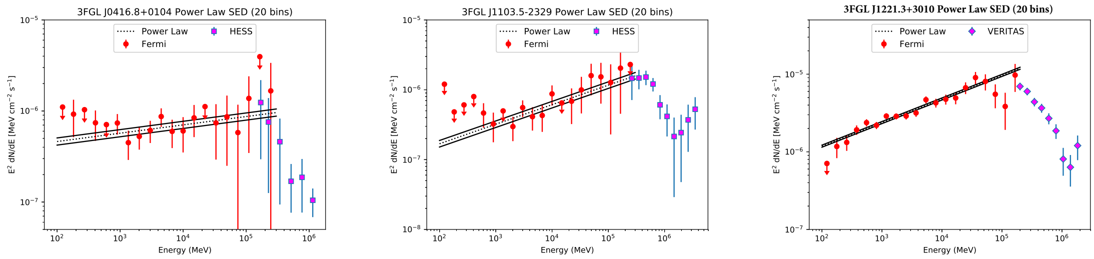
Abstract. Currently there is limited knowledge related to the origin of the intergalactic magnetic fields (IGMF) that permeate the space between galaxies, galaxy clusters and cosmic voids. Understanding the origin of the IGMF is a crucial component in models of galaxies and galaxy cluster formation. This magnetic field can be probed indirectly by its effect on electromagnetic cascades initiated by gamma-gamma absorption of very-high-energy (VHE) gamma rays, produced in blazars, due to its interaction with the extragalactic background light (EBL). The electron-positron pairs produced via this process interact with the intergalactic magnetic field (IGMF) and can be deviated from their original path. These pairs can then Compton-scatter off the cosmic microwave background (CMB) to produce high-energy (HE) gamma rays that may be detected by, e.g., *Fermi*-LAT. The strength of this signal strongly depends on the IGMF strength (B) and the coherence length (λ_B). This secondary gamma-ray emission would be superimposed on the blazars' intrinsic gamma-ray spectrum. A selection of bright blazars will be re-analysed using the upgraded Pass 8 analysis pipeline, to search for this secondary component. This will be used to place constraints on the IGMF strength. The initial results from this project, namely the *Fermi*-LAT analysis of a selection of candidate blazars for this study are presented. The results showed that the light curves and the spectral shape of the SEDs showed negligible variability and that the spectral parameters and fluxes values overlaped within one standard deviation within the results from Finke et al. [12]. This indicates that these are appropriate sources to use for further modelling.

1. Introduction

For a variety of astrophysical objects, like galaxies and galaxy clusters, magnetic fields play a very important role. Observations of Faraday rotation and Zeeman splitting of atomic lines in the radio band and the observations of the polarization of starlight in the optical band, established the existence of galactic magnetic fields with strengths of $1-10$ μG [1, 2]. The cores of galaxy clusters also have magnetic fields of similar strengths [3]. Recently magnetic fields of $10^{-8}-10^{-7}$G have also been discovered outside galaxies and galaxy clusters in the intergalactic space [4, 5].

The galactic magnetic fields, in galaxies and galaxy clusters, are assumed to be caused by the amplification of the weak seed fields that are of cosmological origin. The mechanism of the amplification, nature and origin of these weak seed fields are currently still unknown. By making measurements of these initial seed fields, this process can be constrained. This intergalactic magnetic field (IGMF) can be indirectly measured with gamma-ray telescopes based on its

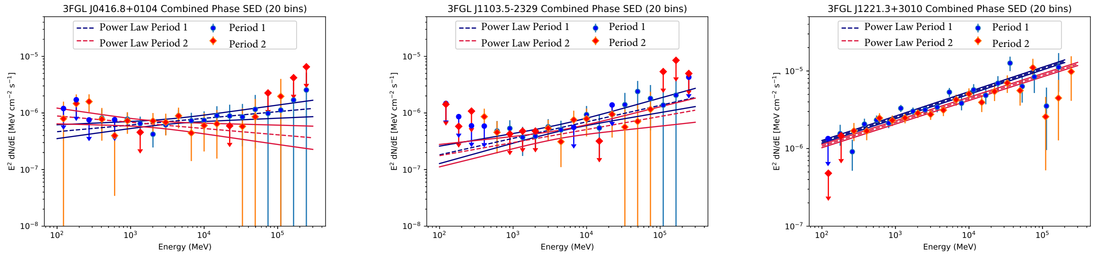


(a) SED for 1ES 0414+009 with Fermi and HESS data [15]. Red dots and pink squares represent the Fermi and HESS data respectively.

(b) SED for 1ES 1101-232 with Fermi and HESS data [16]. The data points are similarly presented as in a).

(c) SED for 1ES 1218+304 with Fermi and Veritas data [17]. Red dots and pink diamonds represent the Fermi and Veritas data respectively.

Figure 3. SEDs for the sources a) 1ES 0414+009, b) 1ES 1101-232 and c) 1ES 1218+304. The black dotted line represents the power-law model fit and the black filled lines represent the power-law model fit with one standard deviation from the dotted line fit.



(a) Combined SED for 1ES 0414+009 with Fermi and HESS data for the Period 1 (2008/08/04 to2013/07/12) and Period 2 (2014/07/08 to 2018/01/01) time periods.

(b) Combined SED for 1ES 1101-232 with Fermi and HESS data for the Period 1 (2008/08/04 to 2013/04/13) and Period 2 (2013/07/12 to 2018/01/01) time periods.

(c) Combined SED for 1ES 1218+304 with Fermi and Veritas data for the Period 1 (2008/08/04 to 2013/04/13) and Period 2 (2013/07/12 to 2018/01/01) time periods.

Figure 4. Combined SEDs for different time periods (Period 1 and Period 2) represented in the figures (blue dots and red diamonds) for the sources a) 1ES 0414+009, b) 1ES 1101-232 and c) 1ES 1218+304. Both time period peroids (Period 1 and Period 2) are fitted with a power-law model, with one standard deviation, reperesented by the dotted and filled lines respectivily (navy and maroon).

4. Results

The variability of each source has been investigated by producing light curves shown in figure 2. SEDs were also constructed during periods of higher and lower activity to compare whether the SEDs remained sufficiently stable and are shown in figure 3 for each source. A power-law, power-law with a super exponential cut off, log parabola, broken power-law and the smooth broken power-law spectrum models were tested for goodness-of-fit. The power-law spectrum model had the overall best Log Likelihood and test statistics (TS) values and also a better fit to the high-energy data points. For each blazar source a light curve, spectral index plot, SED plot and a combined SED plot for different time periods (Period 1 and Period 2) of the light curves, were produced (figure 4). These two time periods were chosen such that Period 1 and Period 2 had a maximum difference in there average spectral index values. All the SED and light curve plots showed little variability in the spectral index value, and the slopes of the spectrum

Power law models in the SED plots, and flux values. Thus all the investigated sources can be considered sufficiently non-variable for the future modelling. The spectral values obtained from all the sources are also consistent with those obtained by Finke et al. [12].

5. Conclusion

The results from all the sources above, for the test statistic (TS) value integrated flux and the spectral index, are all within one standard deviation in agreement with the results obtained from the Finke et al. [12] paper. The errors we have obtained are smaller because of the much higher TS values. This is because we have used approximately 9.5 years of data with Pass 8 where as Finke et al. [12] used approximately 6 years of data with Pass 7. The spectral shape of the sources during different variable time periods (Period 1 and Period 2) in figure 2, showed little variability and the difference in spectral index between the two time periods lies within one standard deviation of one another and the spectral index for the full SED in figure 3. Thus our three sources are stable enough to model the IGMF affecting the VHE cascade spectra of these sources and place constraints on the IGMF strength and coherence length. Data analysis for an additional sample of sources is currently in progress. After this is completed a model based on the work of Arlen et al. (2014) will be developed with the use of the Monte Carlo code from Kachelrieß et al. (2012) to compare to the Fermi data. We will use this to place constraints on the IGMF.

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