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Inter Galactic Magnetic field constraints through the gamma ray observations of the Extreme High-frequency-peaked BL Lac candidate HESS 1943+213

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Extreme High-frequency-peaked BL Lac (EHBL) objects, a subclass of blazars characterised by a synchrotron peak frequency exceeding 10^{17} Hz, and, in some cases, an inverse Compton peak energy exceeding 1 TeV, are ideal sources to study the InterGalactic Magnetic Field (IGMF) due to the hardness of their spectrum. HESS J1943+213 is a Very High Energy (VHE, >100 GeV) γ-ray source shining through the Galactic Plane discovered by HESS. Recently, also VERITAS published a VHE spectrum spanning from 200 GeV up to about 2 TeV consistent with that of HESS within the errors (photon index=2.8). The archetypical EHBL source is 1ES 0229+200 which has a redshift z=0.14 and a similar VHE slope (photon index=2.9). Since the observed flux of HESS J1943+213 at 1 TeV is more than a factor of two larger, and its redshift is bigger (z<0.23), a much larger reprocessed power is expected, which allowed us to study the magnetic field strength with great accuracy. We used the simulation code CRpropa 3 to simulate the cascade emission assuming different IGMF configurations and a detailed analysis of the 10 years of Fermi-LAT data to extend the observed VHE spectrum down to 5 GeV. Comparing the cascade spectrum with the combined spectra from Fermi-LAT and Cherenkov telescopes we derived a lower limit on the IGMF strength of the order of $6{\cdot}10^{-14}$ G which is at least a factor of 4 larger than previously published results obtained with the source 1ES0229+200. Effects of the duty cycle are also taken into consideration.

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1. Introduction

Despite their relevance [1], the origin and time evolution of cosmic magnetic fields are still unknown. One possible scenario proposed by several authors, is that magnetic fields are originated in the early universe as a consequence of phase transitions [2, 3]. If this is the case, those magnetic fields would have served as an initial (seed) field from which also galactic magnetic fields would have amplified up to present-day values, and a weak relic of the primordial magnetic field could be still observed outside structure, in cosmic voids. Despite all the efforts, such a magnetic field has never been observed so far, mostly because of its weakness and the peculiar conditions of the intergalactic medium (IGM) in cosmic voids, which make the constraints obtainable with classical magnetic field tracers rather weak.

The measurement of the IGMF with gamma-ray sources has been first proposed by Plaga [4], and the exploitation of the spectrum of blazars has been first hypothesized by Neronov and Semikoz [5]. The authors proposed to exploit the deflection of electron-positron pairs created in the IGM by the gamma-gamma interaction between high energy photons emitted by a TeV blazar and those of the EBL. Since then, a number of attempts to measure the IGMF have been performed, with results that largely depended on the selection of the source and the hypotheses about its emission.

In this work, we show preliminary results for the constraints obtained on the IGMF with HESS J1943+213 under very conservative hypotheses. Our results increase the existing lower limit to at least $6{\cdot}10^{-14}$G in the stationary source hypothesis, and to at least $6{\cdot}10^{-15}$G in the hypothesis of a flux stability of at least 8 years using 10 years of Fermi-LAT data and a full gamma-band joint VERITAS/HESS/Fermi analysis, as well as a 3D simulation of the propagation of the electromagnetic particles in a turbulent IGMF carried out with CRPropa 3 [6]. Analyses of different geometry of the gamma-ray emission and of the effect of plasma instabilities on this particular source are ongoing.

2. Cosmic magnetic fields

The origin and time evolution of cosmic magnetic fields is unknown. This is especially problematic for galaxies and cluster of galaxies, in which the magnetic field is strong enough to be dynamically important and might have played a role in their evolution[1]. Most theories for the evolution of galactic magnetic fields rely on the generation of small seed fields that might have happened either before or after structures formation, and subsequent amplification phases which would have amplified the magnetic field up to present-day values and can be roughly categorized in primordial and astrophysical models [2, 3]. In the primordial scenario, the IGMF serves as a potential seed field which would set an initial magnetic field value in galaxies, and since it is originated in the early universe, if it survived the expansion phases would be still observable as a weak relic in cosmic voids, where the contamination from outflow of galaxies is inefficient [7, 8] and the magnetic field is supposed to retain its original structure. Conversely, in the often called astrophysical scenario, magnetic seed fields originated at structure formation and amplified later on, owing to a more abrupt magnetic field evolution and no IGMF at all.

3. HESS J1943+213

HESS J1943+213 is an EHBL fortuitously discovered by HESS in its galactic plane survey [9], it is detected also by VERITAS [10] and has an associated source in the Fermi-LAT 4FGL catalogue [11] (4FGL J1944.0+2117) shown in figure 1. Compared to the source that so far gave the strongest lower bounds for the IGMF (1ES 0229+200), HESS J1943+213 has a much stronger flux at TeV energies, which makes it potentially more suitable to study the effect of the IGMF on electron-positron pairs.

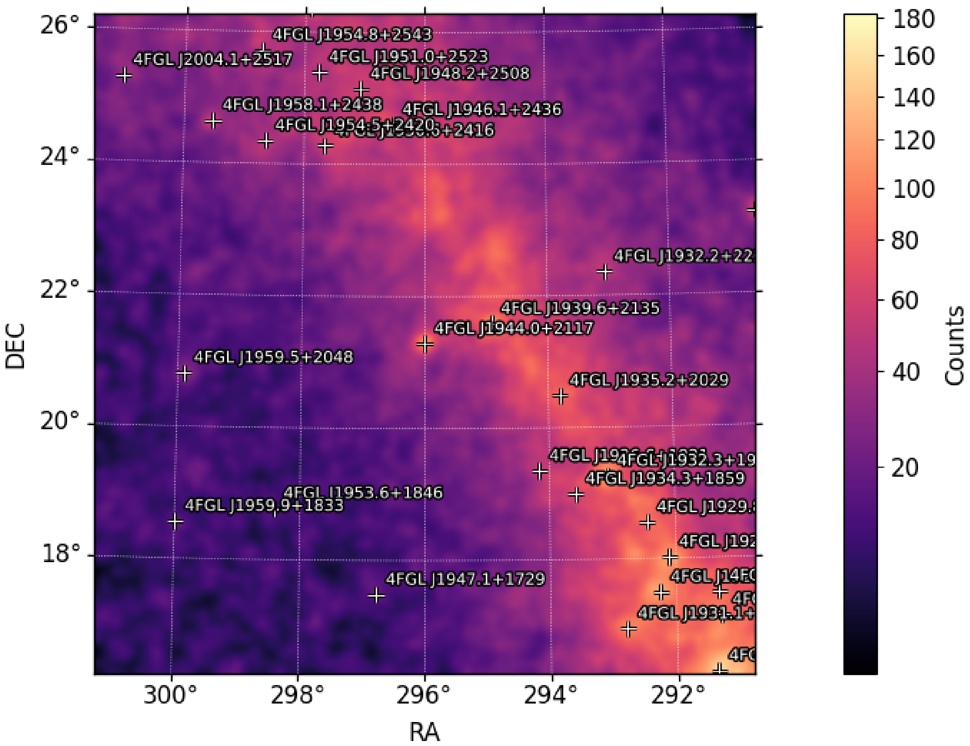

Figure 1: Event map of 10 years of Fermi-LAT data around the source, here labelled with its 4FGL catalogue name, 4FGL J1944.0+2117

4. Joint analysis

The HESS/VERITAS band has been used to infer a conservative estimate of the intrinsic spectrum of HESS J1943+213 to be used as an injection spectrum for the simulations with the following argument: the IGMF is constrained by the minimum strength required to deplete the cascade flux in order to be compatible with the low energy gamma-ray observations, hence a smaller expected cascade emission will require a smaller magnetic field, therefore a smaller VHE flux is expected to lead to a smaller lower limit for the IGMF. For this reason, we imposed an exponential cut-off to the intrinsic model as defined in equation 1 and run a confidence level-based consistency check limiting ourselves to the last accepted model that gave the smallest expected cascade power P defined as $P = \int_{300GeV}^{\infty} E\frac{dN}{dE}dE$, which constrained the three parameters of the model, most notably its slope γ =1.5 and the cut-off energy E_{cut}=2080 GeV.

$$\frac{dN}{dE} = N_{300}\left(\frac{E}{300GeV}\right)^{-\gamma} e^{-E/E_{cut}} \tag{1}$$

The 10 years point source Fermi-LAT analysis has then been used to check the consistency of the low-energy extrapolated intrinsic spectrum summed to the expected cascade emission: the magnetic field has then been increased until consistency was reached. Since the stability of the source is not assessed over long time scales, we also obtained a smaller lower limit in the hypothesis of a stability limited to 8 years, which is the time interval for which the source has been observed to be stable by VERITAS and HESS, by ignoring all cascade photons that delayed more than 8 years with respect to unabsorbed ones.

5. Simulation of the cascade emission

The simulation of the emission, propagation and interaction of photons and electromagnetic particles have been simulated with the CRPropa 3 [6] code with all the relevant interactions for the development of a cascade, a Franceschini [12] model for the EBL and a turbulent magnetic field with a Kolmogorov spectrum generated with the built-in module. The source was set up as a narrow beam of 10^5 photons randomly generated with a power-law distribution with an exponential cut-off represented by our injection spectrum propagated through a turbulent magnetic field with a Kolmogorov spectrum of 10Mpc coherence length for which we increased the strength until the conditions explained in section 4 for the reconstructed flux were reached.

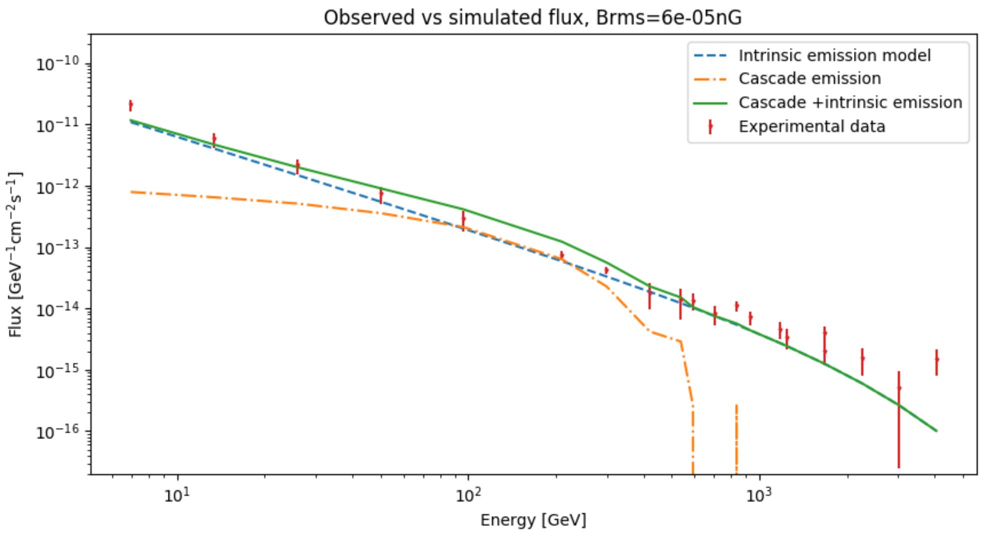

Figure 2: Intrinsic, cascade and cascade + intrinsic model plotted along the de-absorbed data for our conservative model induced lower limit for the IGMF. The $\Delta\chi^2$ of the cascade+intrinsic is of 3.3, and is therefore more conservative than our threshold of 2.7 or 90% CL.

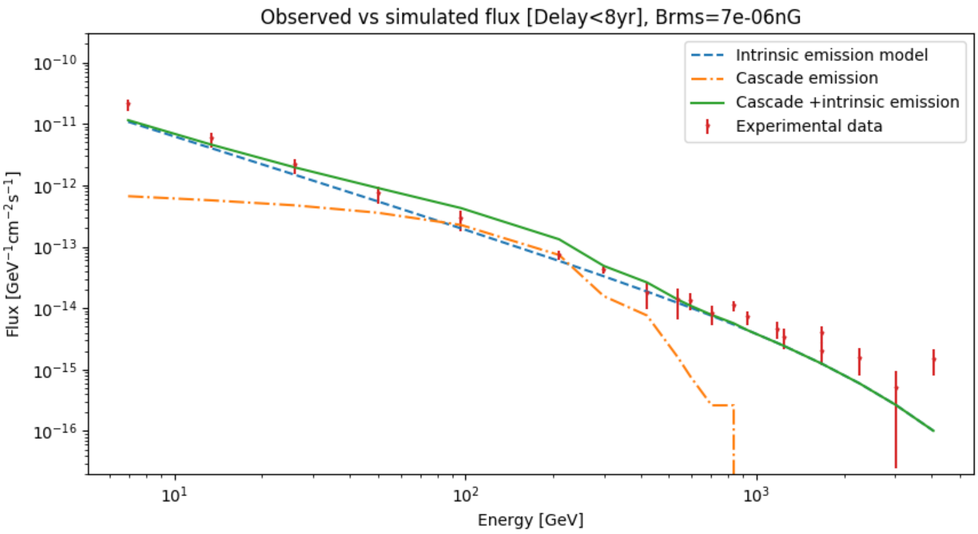

Figure 3: Same analysis of figure 2 but with an activity time of 8 years. This time the compatible lower limit is increased to $7{\cdot}10^{-15}$G, with a $\Delta\chi^2 = 4.2$

6. Conclusions

Our results confirm and strengthen the IGMF hypothesis. The analysis that we performed provides a lower limit of $6{\cdot}10^{-14}$ and $6.5{\cdot}10^{-15}$ in the hypothesis of long and short stability time respectively as described in section 4 and as show in figg. 2 and 3. However, the effectiveness of the cascading process to sample the IGMF is a matter of debate, as other mechanisms such as plasma instabilities might partially cool the electron-positron beam more efficiently than the inverse Compton effect, preventing part of the cascade from being developed and mimicking the effect of a stronger IGMF, but the results obtained by several authors are often contradictory [13, 14]. Analyses of these effects on the lower limit are ongoing.

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