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Detectability of large correlation length inflationary magnetic field with Cherenkov telescopes

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Gamma-ray measurements can be used to detect Inter-Galactic Magnetic Fields (IGMF) in the voids of Large Scale Structure. We explore the possibility of identifying the inflationary origin of the IGMF and measuring its parameters with gamma-ray astronomy methods. We developed new CRbeam Monte-Carlo code for the precision of the modelling of the secondary gamma-ray emission and compared it with publicly available Monte-Carlo codes ELMAG and CRPropa. We demonstrated that after eliminating the inaccuracies found in ELMAG and CRPropa, the difference between the three codes is reduced to 10% when modelling nearby sources with $z \sim 0.1$. (inaccuracies was taken into account and removed by developers of ELMAG and CRPropa in new versions of their codes). Finally, we argue that the new CRbeam code produce reliable predictions when modelling both nearby and distant sources with $z \sim 1$ and thus provide relevant precision for the prospective CTA studies of gamma-ray sources and IGMF. The large correlation length inflationary field is expected to impose a characteristic asymmetry of extended secondary gamma-ray emission that is correlated between different sources on the sky. New gamma-ray observatory, Cherenkov Telescope Array (CTA), will provide an increase of sensitivity and angular resolution compared to the current generation of telescopes. We show that CTA observations can be used for the test of inflationary origin of the IGMF.

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1. Introduction

Observations of extended and delayed gamma-ray emission around extragalactic sources of TeV γ-rays provides a possibility of measurement of magnetic field in the voids of the Large Scale Structure (LSS) [1, 2]. This emission is generated by electron-positron pairs deposited by the pair production by γ-rays on the Extragalactic Background Light. The combination of data from current generation Cherenkov telescopes, HESS, MAGIC and VERITAS with data from the Fermi-LAT telescope currently constrains the void field strength to be stronger than $\sim 10^{-17}$ G [3, 4]. The next-generation Cherenkov Telescope Array (CTA) will provide a possibility to explore the magnetic field over a wide range of possible strength and correlation lengths, up to the field strength of the order of $B \sim 10^{-11}$ G [5, 6].

Several physical phenomena that took place a fraction of a second after the Big Bang can be responsible for the generation of a relic magnetic field. First order phase transitions that might have happened at quark confinement or during the Electroweak epoch can produce short correlation length magnetic field that evolves through turbulent decay toward a magnetic field configuration with correlation length and strength satisfying a relation $\lambda_B \sim 0.1[B/10^{-12}\text{ G}]$ kpc today [7]. Alternatively, a field generated at the epoch of inflation can have a very large correlation length, up to the present day Hubble scale [8, 9].

Magnetic fields from galactic outflows, if they efficiently pollute the voids (as suggested e.g. by [10]), would be distinguishable from both inflationary and phase transition field based on their galaxy scale correlation length (10-100 kpc). However these outflows are most likely not strong enough to fill the voids [11]. This suggests that the volume-filling magnetic field in the voids is a relic from the Early Universe [12].

In what follows we explore the possibility of distinguishing between these two possibilities observationally. Large correlation length fields break isotropy by selecting a unique direction in a cosmologically large volume. This selected direction imposes a correlated asymmetry on magnetic field dependent extended emission patterns around γ-ray sources across the sky. We explore if it is possible to detect this asymmetry and measure the inflationary magnetic field direction. We use a magnetic field generated from a realistic model of the LSS derived from Borg constrained cosmological simulations [13] that reproduces the location of known LSS elements (galaxies, clusters) in the local Universe. Our analysis relies on magneto-hydrodynamic (MHD) simulations using the ramses code [14] to estimate the effect of the structure formation on the initial magnetic field configuration. Modelling the properties of secondary γ-ray signal is performed with the CRbeam code [15]. We use calculations of electromagnetic cascades along lines of sight to known nearby blazars to estimate the influence of large correlation length magnetic field on the properties of secondary γ-ray signal from the cascade.

2. Modelling of the magnetic field and sources

We calculate intergalactic magnetic field (IGMF) out to a distance of 200 Mpc from the Milky Way by running MHD simulations using the Ramses-MHD code [16] on the initial conditions (ICs) from Borg [17]. Using a Markov Chain Monte Carlo approach, the Borg methodology generates

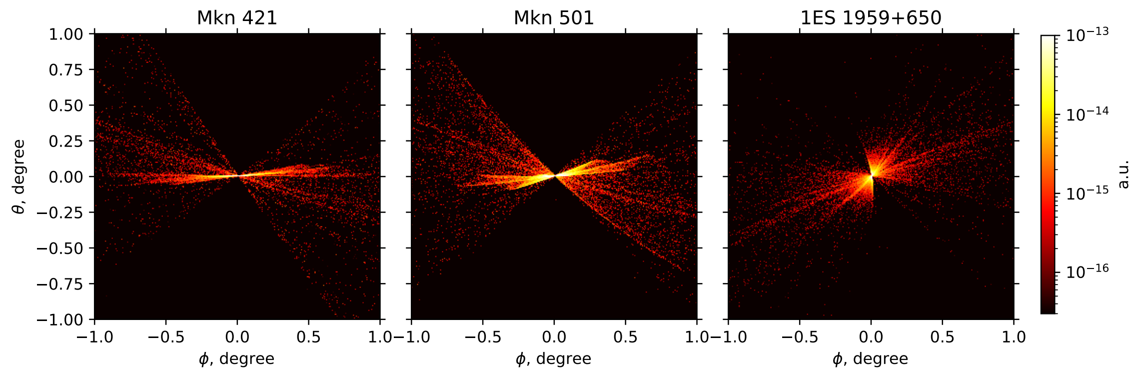

Figure 1: Images of the extended emission signal in the energy range 200 GeV - 2 TeV for the three brightest sources in our sample. The assumed initial cosmological magnetic field strength is $B = 10^{-13}$ G. The direction of the jet axis coincides with the direction from the source to the observer and the jet opening angle is 5°.

ICs that are constrained to reproduce the structure of positions of real galaxies and galaxy clusters of the 2M++ survey [18] within 200 Mpc cube around Milky Way.

There are several known TeV blazars whose position falls within the high resolution simulation volume: Mkn 421, Mkn 501, QSO B2344+514, Mkn 180, 1ES 1959+650, AP Librae, TXS 0210+515. All the sources are well-established TeV emitters. The proximity of the sources enables measurements of their intrinsic spectra attenuated by the pair production effect up to 10 TeV. This is important because the extended emission in the energy range above 100 GeV is produced by electrons and positrons injected in interactions of γ-rays with energies above 10 TeV. Measurement of the flux above 10 TeV allows us to obtain reliable estimates of the expected power of the secondary flux in the $E > 100$ GeV range. In the following sections we show results for the three brightest sources in our sample Mkn 501, Mkn 421 and 1ES 1959+650.

Using simulated MHD cube we checked that selected γ-ray sources are situated in moderately overdense regions that are unlikely to be affected by strong magnetised outflows from galaxies. None of the three sources have a line-of-sight aligned with a filament of the LSS. This makes all the three sources suitable for the IGMF measurement. The component of the magnetic field perpendicular to the line of sight is strongly suppressed in the case of 1ES 1959+650, because of the alignment of the cosmological field direction (the direction toward North) with the line of sight. Finally we checked that the effect of structure formation on the magnetic field direction is moderate and the initial cosmological field direction is mostly preserved in the course of structure formation.

3. Modelling of secondary extended gamma-ray emission

We model the secondary cascade γ-ray signal with the CRbeam Monte Carlo code [15]. In [19], we compared the precision of modeling electromagnetic cascades of this newly developed code with the predictions of two other popular codes CRPropa [20] and ELMAG [21]. The modular structure of the CRbeam and CRPropa allows all relevant processes to be tested independently of each other. Specifically, we consider the Breit-Wheeler pair production and inverse Compton scattering on the EBL and CMB. For each interaction, we compare interaction rate and energy

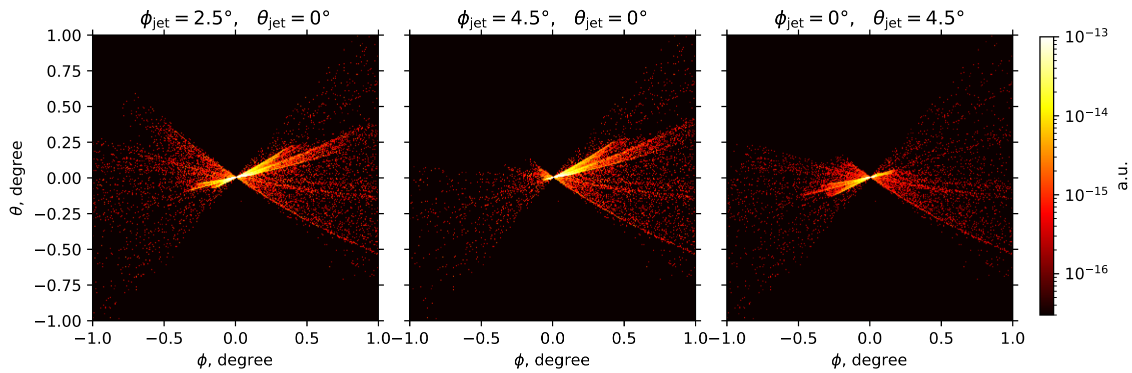

Figure 2: Images of the extended emission signal around Mkn 501 for different directions of the jet axis with respect to the projected direction of the cosmological magnetic field. Magnetic field strength, energy range and jet opening angle are the same as in Fig.1.

distribution of secondary particles inferred from simulations with the theoretical predictions. Also, disabling all interactions makes it possible to compare the propagation of electrons in a magnetic field. For ELMAG, on the contrary, such independent testing of interactions is impossible, therefore we use the results of simulations with ELMAG to compare the properties of the cascade signal, when all relevant interactions are turned on.

We find that the predictions for the spectral, imaging, and timing properties of the secondary emission may differ by about 50% in the CTA's energy range of interest. We trace the origin of some of these discrepancies and find that they can be reduced after corrections. In particular, for relatively nearby sources with a redshifts $z \sim 0.15$, the discrepancies between all three codes (CRbeam, CRPropa, and ELMAG) are down to 10% in all our tests after introducing corrections. We find, however, that the scatter of the predictions increases substantially with increasing redshift even when our corrections are applied. We argue that the main reason for the remaining discrepancies is the implementation of cosmological evolution of the EBL in CRPropa, which still lead to non-negligible differences between model calculations for sources at large redshifts.

Thus we conclude that CRbeam provides the most accurate modeling of the cascades and we use it to calculate secondary emission of the selected sources. For intrinsic point source spectrum we assume broken power law spectrum with break position around 100 GeV and maximum energy 100 TeV and adopted the EBL model of [22]. To explore different strengths of seed magnetic field we rescale the magnetic field profile towards the source by a constant factor keeping the shape of the profile unchanged.

4. Results

Figs. 1 shows the images of the extended emission calculated for the field strength 10^{-13} G for the three brightest sources in our sample. The images of extended emission around Mkn 421 and Mkn 501 reveal a clear overall azimuthal asymmetry that is imposed by the orientation of the initial homogeneous field projected on the sky. To the contrary, the image for 1ES 1959+650 appears halo-like. This is explained by the alignment of the magnetic field along the line of sight.

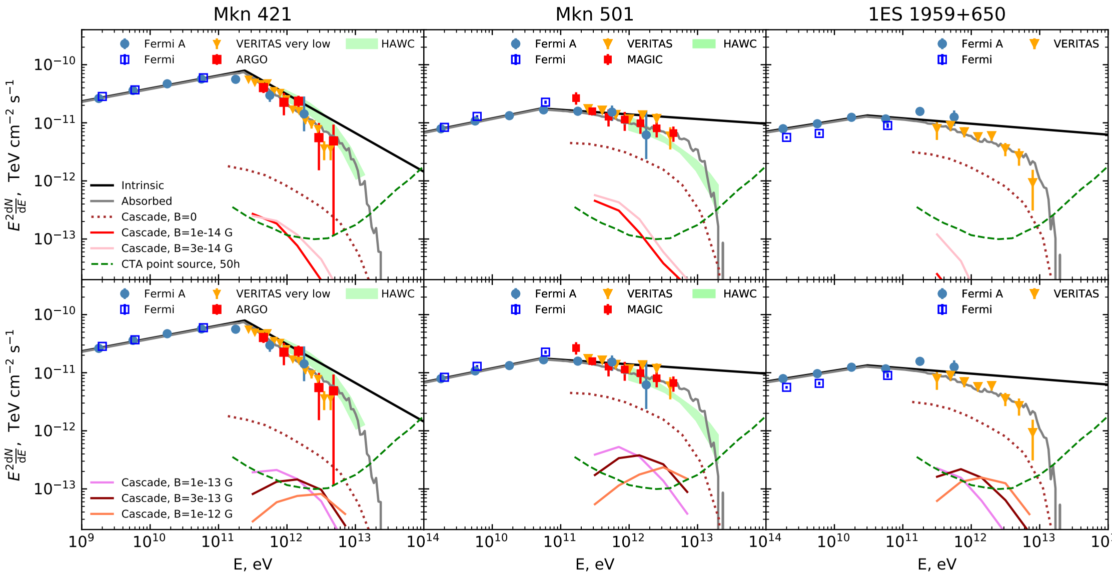

Figure 3: Spectra of intrinsic point source and extended emission for different assumed magnetic field strengths (**upper panels:** 0, 10^{-14} **and** 3×10^{-14} **G, lower panels:** $10^{-13}, 3 \times 10^{-13}$ **and** 10^{-12} **G)** , for the three brightest sources in the sample. Point source spectra from Fermi LAT, MAGIC [23], VERITAS [23] ARGO [24] and HAWC [25]. Total flux from the cascade in case $B = 0$ is shown with dotted line. Extended emission outside of the PSF of point source is shown with colored lines for magnetic fields between 10^{-14} G and 10^{-12} G. Dashed green line show sensitivity of CTA to point sources.

The images are superpositions of line-like features that are not perfectly aligned with each other. If the IGMF were perfectly homogeneous, with fixed direction, all these features would be strictly aligned, so that "narrow-jet-like" extensions would be observable. The appearance of multiple misaligned features reveals the influence of the structure formation on the field.

If the blazar jet is closely aligned with the line of sight, the two sides of the extended emission are symmetric, they have comparable surface brightness (see Fig. 1). This symmetry can be broken by the misalignment of the jet with the line of sight. This effect is illustrated in Fig. 2. Angles between the blazar jet, the line of sight and the direction of IGMF regulate the flux levels of the extended emission components on different sides.

The orientation of the two-sided extension that is due to the presence of the large correlation length field is, always perpendicular to the direction of magnetic field projected on the sky. If the cosmological IGMF is correlated on the distance scales larger than hundreds of Megaparsecs, orientations of the two-sided extensions around different sources all over the sky are all expected to be aligned. Measurement of aligned extended emission features around multiple sources can provide an unambiguous evidence for the presence of magnetic field of inflationary origin and provides the direction of the primordial field.

Fig. 3 shows spectra of the point and extended source emission for different assumptions about the magnetic field strength. For each source we choose the model of the intrinsic spectrum in such a way that it fits the spectral measurements of the "low state" of the source and/or the time-averaged spectral measurements on multi-year time scales. For all sources we consider two alternative Fermi spectral data: the spectral measurements reported in the Fermi source catalog [26] and the spectra extracted usng the aperture photometry approach for the full 13-year exposure of Fermi/LAT up to July 2021. This allows us to extend the Fermi catalog measurements up to the 3 TeV energy.

For Mkn 501 we used MAGIC and VERITAS analyses from 2009 [23], and long term observations from ARGO [24] and HAWC [25]. For Mkn 421 we used long term observations from ARGO [27] and HAWC [25] and very low state from VERITAS measurement [28].

We extracted the extended source fluxes from wedges of the angular width 0.3° that contain the signal. From the wedges, we excluded the regions in which the primary source emission dominates, namely, we did not take into account those regions of the wedges that are located at a distance from the centers less than the angular resolution of the CTA. From Fig. 1 one can judge that the extended emission is dominated by the flux in a much narrower wedge, with opening angle of just a few degrees.

This gives a conservative estimate of the detectable extended source flux. The linear, one-dimensional, rather than circular, two-dimensional shape of the extended source also provides an improvement of sensitivity. Concentration of the extended signal in a narrow wedge reduces the solid angle and hence increases the signal-to-noise ratio.

Fig. 3 shows a comparison of the expected secondary flux levels with the sensitivity of the CTA telescopes for detection of extended sources. This comparison shows how challenging the search for the two-sided jet-like extensions might be. The model predictions for the extended signal are at the limit of sensitivity for the 50 hr exposure of each of the three brightest sources in our source sample. However, use of possible improvements of the method with "in-situ" measurement of the telescope point spread function and careful choice of the wedge for the extended signal measurements may improve the sensitivity. Otherwise, much longer exposure of several hundred hours (instead of 50 hr considered here) can also boost signal-to-noise ratio and make the correlated extended emission signal measureable in all the three brightest nearby blazars considered above.

5. Conclusions

We studied a possibility of detection of primordial magnetic field from inflation [8, 12] with gamma-ray telescopes. Such field can be coherent on cosmological scales and induce wedge-like extended emission around nearby blazars, with aligned wedge orientations in multiple sources across the sky.

This alignment can be used to distinguish the establish the inflationary origin of IGMF, because it is not expected if the IGMF originates from cosmological phase transitions. For small coherence scale IGMF, the wedge like appearance of the extended emission is also generically expected, but the position angles of wedged extended emission around different sources would not be correlated, because it is determined by the orientation of the jets in the primary blazar source.

The morphology of the secondary emission depends on the jet orientation also for the inflationary magnetic field (Fig. 2). However, the jet orientation does not affect the position angle of the extended source.

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