

A method of measurement of extragalactic magnetic fields by TeV gamma ray telescopes

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We propose a method of measurement of extragalactic magnetic fields in observations of TeV γ rays from distant sources. Multi-TeV γ rays from these sources interact with the infrared photon background producing secondary electrons and positrons, which can be just slightly deflected by extragalactic magnetic fields before they emit secondary γ rays via inverse Compton scattering of cosmic microwave background photons. Secondary γ rays emitted toward an observer on the Earth can be detected as extended emission around initially point source. Energy dependent angular profile of extended emission is related to the strength of extragalactic magnetic field along the line of sight. Small magnetic fields $B \leq 10^{-12}$ G in the voids of the large scale structure can be measured in this way.

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The problem of the origin of 1–10 μ G magnetic fields in galaxies and galaxy clusters is one of the long standing problems of astrophysics/cosmology (see [1] for a review). Such fields are thought to be produced either via dynamo mechanism [2] or via compression of primordial magnetic field during the large scale structure (LSS) formation [1]. In either of these two scenarios one assumes the existence of a small “seed” primordial magnetic field of cosmological origin. The assumed strength of the primordial magnetic field and its correlation length are strongly model dependent. Moderate experimental limit on the present day strength of primordial magnetic field $B_{pr} < 10^{-9}$ G comes from the limit on rotation measure of emission from distant quasars, assuming (largely uncertain) correlation length $l_c \sim 1$ Mpc [3]. Similar restriction comes from the analysis of anisotropies of the cosmic microwave background (CMB) [4].

Recently a significant progress was achieved in calculations of the tree-dimensional structure of extragalactic magnetic fields (EGMF) [5, 6]. These calculations are based on the numerical simulations of LSS formation. The main result of the magnetic field simulations is that, similarly to the LSS, the magnetic field structure is filamentary, with large voids, filaments and knots. The strength of the primordial magnetic field in these simulations is chosen in such a way as to reproduce the measured fields $B \sim 1 \mu$ G in Galaxy clusters. New simulations allow to estimate the cumulative volume filling factor $\mathcal{V}(B)$ for EGMF with the strength close to a typical

value B . One should note that the results of simulations by different groups differ dramatically. In particular, in Ref. [5] it is claimed that $\mathcal{V}(B > 10^{-9}$ G) $\simeq 0.15$, while $\mathcal{V}(B < 10^{-12}$ G) $\simeq 0.07$. To the contrary, in Ref. [6] $\mathcal{V}(B > 10^{-9}$ G) $\simeq 2 \cdot 10^{-4}$ while $\mathcal{V}(B < 10^{-12}$ G) $\simeq 0.7$. Recent independent calculation of ref. [7] suggests that $B > 10^{-9}$ G fields fill $\sim 1\%$ of volume, which is somewhat in between of the results of Refs. [5, 6].

Obviously, the best way to resolve the above controversy of numerical calculations is to measure the EGMF outside the galaxies and galaxy clusters. In this paper we propose an alternative way of measurement of EGMF which is sensitive to the very weak magnetic fields $B \leq 10^{-12}$ G and, therefore, could be used to probe, for the first time, the magnetic fields in the voids of the LSS. Thus, one obtains a unique opportunity to measure the “primordial” or “seed” magnetic field which is explicitly implied in most of the models of generation of magnetic fields in galaxies and galaxy clusters.

The idea is to look for the extended TeV γ -ray emission around distant sources. It is known that multi-TeV γ -rays from these sources could not reach the Earth directly because of the pair production on the extragalactic (infrared) background light (EBL). The pair production on EBL should lead to the exponential suppression of the γ -ray flux from the source,

$$F(E_{\gamma 0}) = F_0(E_{\gamma 0}) \exp[-\tau(E_{\gamma 0}, z)]. \quad (1)$$

Here $F(E_{\gamma 0})$ is the detected spectrum, $F_0(E_{\gamma 0})$ is the initial spectrum of the source and $\tau(E_{\gamma 0}, z)$ is the optical depth with respect to the pair production on EBL, which is a function of the primary photon energy $E_{\gamma 0}$ and of the redshift of the source z [8]

$$\tau = 5 \div 10 \left[\frac{z}{0.1} \right] \left[\frac{\rho_{IR/O}}{(5 \div 10) \text{nW/m}^2 \cdot \text{sr}} \right] \left[\frac{E_{\gamma 0}}{10 \text{ TeV}} \right] \quad (2)$$

(we allow for an uncertainty of about a factor of 2 in the density of the infrared/optical background, $\rho_{IR/O}$, taking into account the recent controversy in the measurements of COBE/DIRBE and the upper limits on $\rho_{IR/O}$ imposed by the TeV observations of distant blazars [9]).

The e^+e^- pairs produced in interactions of multi-TeV γ -rays with EBL photons produce secondary γ -rays via inverse Compton scattering (ICS) of the CMB photons to the energies

$$E_{\gamma} = \frac{4}{3} \epsilon_{CMB} \frac{E_e^2}{m_e^2} \simeq 1.2 \left[\frac{E_{\gamma 0}}{40 \text{ TeV}} \right]^2 \text{ TeV}. \quad (3)$$

(Here $\epsilon_{CMB} = 6 \cdot 10^{-4} \text{ eV}$ is the typical energy of CMB photons. We also have assumed that the energy of primary γ -ray is $E_{\gamma 0} \simeq 2E_e$.) Upscattering of the infrared/optical background photons gives sub-dominant contribution to the ICS because the energy density of CMB, $\rho_{CMB} \sim 10 \div 100 \rho_{IR/O}$, is much higher than the density of the infrared/optical background.

It is conventionally assumed that as soon as trajectories of electrons are deflected by the EGMF, the secondary photons are not emitted in the direction toward the Earth and do not reach the telescope. However, the above way of reasoning is correct only if one calculates only the reduction of the flux of photons emitted initially exactly in the direction of observer. Deflections of electrons produced by the γ -rays which were initially emitted slightly away from the observer, could lead to "redirection" of the secondary cascade photons toward the observer. This effect leads to the appearance of additional "cascade" contribution to the source flux.

The cascade contribution can be distinguished from the "primary" source contribution with the help of imaging capabilities of the TeV Cherenkov telescopes. The secondary cascade γ -rays are emitted at large distances from the source, from an extended conical region (blue shaded region in Fig.1). The opening angle of the cone is determined by the deflection angle of secondary electrons, δ , its vertex coincides with the point source, and its height is equal to the mean free path $D_{\gamma 0} = D/\tau \simeq 10 \div 20 [E_{\gamma 0}/40 \text{ TeV}]^{-1} \text{ Mpc}$ (D is the distance to the source) of the multi-TeV photons through the EBL. Since the line of sight is located inside of the cone, the

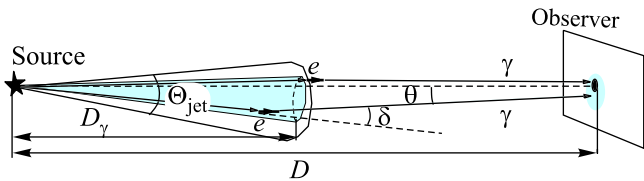


Fig.1. Schematic representation of formation of extended TeV emission around a distant point source due to the cascade on the EBL in small EGMF

cone appears as an extended emission around the initial point source (Fig.1).

The mean free path of the secondary electrons with respect to the ICS of CMB photons, $\lambda_e = (\sigma_T n_{CMB})^{-1} \simeq 1 \text{ kpc}$ ($\sigma_T = 6.7 \cdot 10^{-25} \text{ cm}^2$ is the Thomson crosssection and $n_{CMB} = 411/\text{cm}^3$ is CMB photon density), is much shorter than $D_{\gamma 0}$ and one can assume that electrons immediately re-emit γ -rays via the ICS. The deflection angle of electrons, δ , is determined by the ratio of λ_e to the Larmor radius in the EGMF of the strength B , $r_L \simeq 6.6 \times 10^{22} [E_e/20 \text{ TeV}] [10^{-12} \text{ G/B}] \text{ cm}$. Assuming $\lambda_e \ll r_L$ one can find $\delta \simeq \lambda_e/r_L = 3.2^\circ [20 \text{ TeV}/E_e] [B/10^{-12} \text{ G}]$. A simple geometrical calculation shows that the angular size of extended emission produced via redirection of cascade photons toward the Earth is (see Fig.1)

$$\theta_{\text{ext}} \simeq \frac{D_{\gamma 0}}{D} \delta = \frac{3.2^\circ}{\tau(E_{\gamma 0}, z)} \left[\frac{1 \text{ TeV}}{E_{\gamma}} \right]^{1/2} \left[\frac{B}{10^{-12} \text{ G}} \right] \quad (4)$$

(throughout the paper we use the relation between the primary photon energy, $E_{\gamma 0}$, the energy of secondary electron, E_e and of the secondary photon, E_{γ} given by Eq. (3)).

Comparing the distance covered by the photons which come directly from the point source with the distance covered by (primary and secondary) cascade photons, one can find (from the same geometrical calculation) the typical time delay of the secondary photons is $t_d \simeq \delta^2 D (\tau - 1) / 2\tau^2$. Contrary to the point source flux, the flux in the cascade component is not variable, since it is equal to the point source flux averaged over a large time scale t_d (e.g. for $\delta \sim 5^\circ$, $z = 0.03$ and $E_{\gamma 0} \sim 40 \text{ TeV}$, one obtains $t_d \sim 10^5 \text{ yr}$).

Since each secondary cascade photon carries only a small fraction of the primary photon energy (see Eq. (3)), the flux of the extended source, integrated over the region of the angular size θ_{ext} is a small fraction $\alpha \simeq 2E_{\gamma}/E_{\gamma 0} \simeq 0.06 [E_{\gamma 0}/40 \text{ TeV}]$ of initial point source flux $F_0(E_{\gamma 0})$. The extended source flux is suppressed at high energies because the secondary cascade photons can themselves produce pairs in interactions with EBL photons. The suppression factor is $\exp(-\tau(E_{\gamma}, z))$ where τ

is given by (2). Apart from the absorption at high energies, the spectrum of the extended source is modified if only a fraction of the mean free path of the primary γ -ray, D_{γ_0} , goes through the voids with small magnetic field. This fraction can be expressed through the volume filling factor of the voids, \mathcal{V} , as $D_{\text{voids}}/D_{\gamma_0} \simeq \mathcal{V}^{1/3}$. Combining all the correction/suppression factors one can find a relation between the time-averaged point source flux $\langle F(E_{\gamma_0}) \rangle$ and the flux of extended source integrated over the region $\theta < \theta_{\text{ext}}$:

$$F_{\text{ext}}(E_{\gamma}, \theta_{\text{ext}}) \simeq 0.06 \mathcal{V}^{1/3} \frac{e^{\tau(E_{\gamma_0}, z)} - 1}{e^{\tau(E_{\gamma}, z)}} \left[\frac{E_{\gamma}}{1 \text{ TeV}} \right]^{1/2} \langle F(E_{\gamma_0}) \rangle. \quad (5)$$

Cascade electrons loose all their energy after upscattering of many CMB photons over the “energy attenuation” distance $\Lambda_e \sim (E_e/E_{\gamma}) \lambda_e \sim 20 [20 \text{ TeV}/E_e] \lambda_e$. ICS emission produced by these electrons over the distance $\Lambda_e > \lambda_e$ forms and extended “tail” around the “core” of the extended source, $\theta < \theta_{\text{ext}}$. Since for electron propagation distances $d < \Lambda_e$ the deflection angle scales linearly with d , the surface brightness profile of the tail can be found by integrating the ICS energy loss along electron trajectory, $\mathcal{S}(\theta) \sim \theta^{-1} (1 + 2\theta/\Theta_{\text{ext}})$, where Θ_{ext} is the opening angle of a cone into which the ICS photons produced by the cascade electrons over the energy attenuation length are emitted, $\Delta = \Lambda_e/r_L \simeq \simeq 6^\circ [20 \text{ TeV}/E_e]^2 [B/10^{-13} \text{ G}]$. Using Fig.1 one finds

$$\Theta_{\text{ext}} = \frac{\Delta}{\tau} \simeq \frac{0.6^\circ}{\tau(E_{\gamma}, z)} \left[\frac{1 \text{ TeV}}{E_{\gamma}} \right] \left[\frac{B}{10^{-14} \text{ G}} \right]. \quad (6)$$

The fraction of the total flux of extended source integrated over the region $\theta < \Theta_{\text{ext}}$ is about the initial point source flux $\langle F_0(E_{\gamma_0}) \rangle$ modified at the high energies by the effect of absorption of the secondary γ -rays and by the volume-filling-dependent factor $\mathcal{V}^{1/3}$,

$$F_{\text{ext}}(E_{\gamma}, \Theta_{\text{ext}}) \simeq \mathcal{V}^{1/3} \frac{e^{\tau(E_{\gamma_0}, z)} - 1}{e^{\tau(E_{\gamma}, z)}} \langle F(E_{\gamma_0}) \rangle \quad (7)$$

(compare with Eq. (5)).

Up to now we have assumed that the primary γ -rays are emitted by the point source isotropically. However, most of the distant sources of TeV γ -rays are blazars. The primary γ -ray emission from blazars is known to be concentrated along the direction of the jet with a typical opening angle $\Theta_{\text{jet}} \sim \Gamma_{\text{jet}}^{-1} \sim 5^\circ$ ($\Gamma_{\text{jet}} \sim 10$ is the typical bulk Lorentz factor of the jet). There is no difference between isotropically and anisotropically emitting source till the development of the cascade on EBL leads to redistribution of directions of secondary γ -rays within a cone with an opening angle smaller than the opening angle of the jet (see Fig.1). However, as soon as the deflected

cascade photons are emitted into a cone with opening angle larger than Θ_{jet} , the flux of extended source becomes suppressed. This leads to a cut-off in the surface brightness profile of the extended source at the angles $\theta > \theta_{\text{cut}}$ where

$$\theta_{\text{cut}} \simeq \frac{D_{\gamma_0}}{D - D_{\gamma_0}} \Theta_{\text{jet}} \simeq \frac{\Theta_{\text{jet}}}{\tau - 1} \quad (8)$$

Suppose that extended sources with characteristic (energy-dependent) surface brightness profiles shown in Fig.2 are found around a number of distant point sources. In this case measuring the extended source pa-

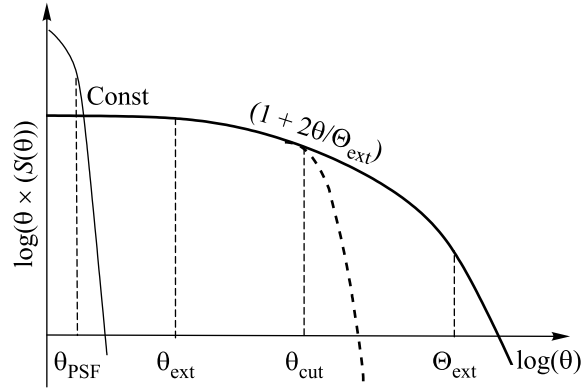


Fig.2. Surface brightness profile of Extended source produce by the cascade on EBL

rameters one can constrain the characteristics of EGMF along the source directions. For example, combining Eqs. (4) and (5) one finds that measurements of $\theta_{\text{ext}}(E_{\gamma})$ and $F_{\text{ext}}(E_{\gamma}, \theta_{\text{ext}})$ provides a measurement of the volume filling factor $\mathcal{V}(B)$ of EGMFs of particular strength B :

$$B \simeq 10^{-13} \tau(E_{\gamma_0}, z) \left[\frac{E_{\gamma}}{1 \text{ TeV}} \right]^{1/2} \left[\frac{\theta_{\text{ext}}}{0.5^\circ} \right] \text{ G}, \quad (9)$$

$$\mathcal{V}(B) \simeq 1 \left[\frac{F_{\text{ext}}(E_{\gamma}) e^{\tau(E_{\gamma}, z)}}{0.06 \langle F(E_{\gamma_0}) \rangle e^{\tau(E_{\gamma_0}, z)}} \right]^3 \left[\frac{1 \text{ TeV}}{E_{\gamma}} \right]^{3/2}.$$

Otherwise, from (6), (7) one finds that information about B , $\mathcal{V}(B)$ can be extracted from the measurement of $\Theta_{\text{ext}}(E_{\gamma})$, $F_{\text{ext}}(E_{\gamma}, \Theta_{\text{ext}})$:

$$B \simeq 10^{-14} \tau(E_{\gamma_0}, z) \left[\frac{E_{\gamma}}{1 \text{ TeV}} \right] \left[\frac{\Theta_{\text{ext}}}{0.6^\circ} \right] \text{ G}, \quad (10)$$

$$\mathcal{V}(B) \simeq \left[\frac{F_{\text{ext}}(E_{\gamma}, \Theta_{\text{ext}}) e^{\tau(E_{\gamma}, z)}}{\langle F(E_{\gamma_0}) \rangle e^{\tau(E_{\gamma_0}, z)}} \right]^3.$$

Determination of characteristics of EGMF from either (9) or (10) constitutes the essence of the proposed method of measurement of EGMF.

The maximal EGMF strength which can be probed is found from observation that if θ_{ext} should not be larger than θ_{cut} . Since $\theta_{\text{ext}} \sim E^{-1/2}$ (see (4)), the maximal EGMF strength is determined by the condition that $\theta_{\text{ext}}(E_{\text{max}}) < \theta_{\text{cut}}$ where E_{max} is the highest energy at which a source is detected. Combining (4) and (8) one finds

$$B_{\text{max}} \simeq 3 \cdot 10^{-12} \frac{\tau(E_{\gamma_0}, z)}{\tau(E_{\gamma_0}, z) - 1} \left[\frac{E_{\text{max}}}{10 \text{ TeV}} \right]^{1/2} \left[\frac{\Theta_{\text{jet}}}{5^\circ} \right] \text{ G.} \quad (11)$$

The weakest magnetic fields which can be probed is found from observation that θ_{ext} can not be measured if it becomes smaller than the size of the point spread function of the telescope, θ_{PSF} . Since $\theta_{\text{ext}} \sim E_{\gamma}^{-1}$ (see (6)), the largest source extension is achieved at lowest energies. Taking into account that for present generation instruments the low energy threshold is situated at the energies $E_{\text{min}} \sim 100 \text{ GeV}$ and that the typical point spread function of a Cherenkov telescope has the size $\theta_{\text{PSF}} \sim 0.1^\circ$, one finds from (6) and (10)

$$B_{\text{min}} \simeq 10^{-16} \tau(E_{\gamma_0}, z) \left[\frac{E_{\text{min}}}{100 \text{ GeV}} \right] \left[\frac{\theta_{\text{PSF}}}{0.1^\circ} \right] \text{ G} \quad (12)$$

As an example of implementation of the proposed method of measurement of EGMF, let us find the constraints on $\mathcal{V}(B)$ imposed by the non-observation of extended emission around Mkn 501 by HEGRA. An upper limit on the extended emission flux within 0.5° around Mkn 501, $F_{\text{ext}, 0.5^\circ} < 10^{-3} F_{\text{flare}}$ (F_{flare} is the flux from Mkn 501 in the flaring state) was derived by HEGRA collaboration [10]). Unfortunately, neither the energy dependence of the derived upper limit nor the assumed surface brightness profile are reported in [10]. We assume in the following that the restriction was put on the flux in the core of the extended source, $\theta < \theta_{\text{ext}}$. The quiescent flux of Mkn 501 is about 10 times lower than the flux in the flaring state which means that HEGRA observation imposes a restriction on the extended emission flux at the level of $F_{\text{ext}}(0.5 \text{ TeV}, \theta_{\text{ext}}) < 0.01 \langle F(0.5 \text{ TeV}) \rangle$. The primary γ rays which produce extended emission at $E_{\gamma} \simeq 0.5 \text{ TeV}$ have energies $E_{\gamma_0} \simeq 26 \text{ TeV}$. Optical depth for such γ rays is large, $\tau(26 \text{ TeV}, 0.03) = 4-8$ (see (2)) even for the relatively nearby source Mkn 501 ($z = 0.03$). The spectrum of Mkn 501 is characterized by the photon index $\Gamma = 2.3 \pm 0.2$ [11], which means that $\langle F_0(26 \text{ TeV}) \rangle \simeq 0.3 \langle F_0(0.5 \text{ TeV}) \rangle$ or

$$E_{\text{ext}}(E_{\gamma}, \theta_{\text{ext}}) < 0.03 \langle F(E_{\gamma_0}) \rangle e^{\tau(E_{\gamma_0}, z)}. \quad (13)$$

Using Eq. (9) one finds that the magnetic field strength probed by the study of extended emission at $E_{\gamma} \simeq 0.5 \text{ TeV}$ at the angular scale $\theta_{\text{ext}} \simeq 0.5^\circ$ is

$B \sim (3 \div 6) \cdot 10^{-13} \text{ G}$. Substituting (13) into (9) one finds

$$\mathcal{V}[B \simeq (3 \div 6) \cdot 10^{-13} \text{ G}] < 0.4 \quad (14)$$

which is much above the predictions of Ref. [5] ($\mathcal{V}(B \simeq 10^{-12} \text{ G}) \sim 0.07$) and is just about the prediction of Ref. [6] ($\mathcal{V}(B \simeq 10^{-12} \text{ G}) \sim 0.7$). The above example shows that with modern telescopes, like HESS, MAGIC and VERITAS, one has a real possibility to detect or put tight constraints on the EGMF in the $10^{-16}-10^{-12} \text{ G}$ range if one makes a systematic search of extended emission around a large number of point sources at different energies and different angular scales.

Electromagnetic cascades of multi-TeV photons on EBL were considered before in a different context. If the cascade happens directly in or near the source, secondary electrons and positrons will be completely randomized in relatively large magnetic fields, $B > 10^{-9} \text{ G}$, producing $R > 1$ Mpc-size halo around the source [12]. In an opposite case, when EGMF is extremely small, $B < 10^{-18} \text{ G}$, all the cascade will proceed in the forward direction and just contribute to the point source flux (even during the flares) [13, 14]. Contrary to both those cases we are interested here in magnetic fields in the intermediate range $10^{-16} \text{ G} < B < 10^{-12} \text{ G}$, in the voids of LSS, and stress that such fields can be *measured* by detection of the time independent extended emission structures around observed TeV point sources.

To summarize, we have proposed a method of measurement of extra-galactic magnetic fields with the help of TeV Cherenkov telescopes. The idea is to look for extended emission produced by cascading of multi-TeV γ -rays emitted by distant point sources. The extended emission produced by the cascade in relatively weak EGMF is expected to have a characteristic energy-dependent surface brightness profile. Measuring the parameters of this profile enables one to determine the characteristic of EGMF from Eqs. (9) and/or (10). The method is sensitive to EGMF strength in the range $10^{-16} \text{ G} < B < 10^{-12} \text{ G}$.

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