Detection of the extragalactic magnetic fields with gamma-rays

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in collaboration with A. Neronov, A. Elyiv, M. Kachelries and S. Ostapchenko
1. Existing limits on EGMF

2. Electromagnetic cascade in intergalactic medium
   - the role of Extra Galactic Magnetic Fields (EGMF)

3. Detection of EGMF by gamma-ray telescopes. 3 methods

4. Evidence for existence of non-zero EGMF from Fermi non-detection of the cascade emission

5. Models of the origin of magnetic fields in the Universe and future detection of EGMF by gamma-ray telescopes
Constraints on the extragalactic magnetic fields
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- If strong EGMF were produced before recombination epoch, they would leave imprint on the CMB anisotropies.
Magnetic fields in spiral and elliptical galaxies reach 1-10 µG.

Galactic magnetic fields are thought to be produced via “α-ω dynamo” amplification of “seed” magnetic fields of the strength $B \geq 10^{-21} \text{G}$.

Magnetic fields in the cores of galaxy clusters reach 1-10 µG.

Cluster magnetic field are thought to be produced via compression and turbulent amplification of “seed” magnetic fields of the strength $B \leq 10^{-12} \text{G}$.
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Magnetic fields in the cores of galaxy clusters reach 1-10 µG.

Cluster magnetic field are thought to be produced via compression and turbulent amplification of “seed” magnetic fields of the strength $B < 10^{-12} \, G$ and/or by AGN’s.

The “seed” fields might exist in their initial form as EGMF.
Gamma-ray measurements and electromagnetic cascade
Attenuation of γ–rays via pair production on EBL

\[ \gamma + \gamma \rightarrow e^+ + e^- \]

TeV γ-ray

1 eV photon
Attenuation of $\gamma$-rays via pair production on EBL

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Extragalactic Background Light (EBL)
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1 eV photon

ULB, May 28, 2010
Observations of extragalactic TeV $\gamma$-ray sources are commonly used to constrain the EBL density.

Major uncertainties:
- a) unknown intrinsic spectrum of $\gamma$-ray source
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**References:**
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Mazin & Raue 2008
**Electromagnetic cascade in intergalactic medium**

\[ \gamma + \gamma \rightarrow e^+ + e^- \]

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\[ E_\gamma = 0.75 \text{ GeV} \left( \frac{E_e}{0.5 \text{ TeV}} \right)^2 \]
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If the primary $\gamma$-ray was emitted along the line of sight, secondary cascade $\gamma$-rays produced by deflected electrons/positrons are not emitted along the line of sight.
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Electron Larmor radius

\[ R_L = \frac{E_e}{eB} \approx 3 \times 10^{23} \left[ \frac{B}{10^{-13} \text{G}} \right] \left[ \frac{E_e}{10 \text{ TeV}} \right] \text{ cm} \]
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$$B \geq 10^{-13} \text{ G}$$

**Electron Larmor radius**

$$R_L = \frac{E_e}{eB} \approx 3 \times 10^{23} \sqrt{\frac{B}{10^{-13} \text{ G}}} \left( \frac{E_e}{10 \text{ TeV}} \right)^{1/4} \text{ cm}$$

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$$D_e = \frac{3m_e^2}{4\sigma_T U_{\text{CMB}} E_e} \approx 10^{23} \left( \frac{E_e}{10 \text{ TeV}} \right)^{1/3} \text{ cm}$$
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Mazin & Raue 2008
Detection of EGMF with cascade
Production of secondary photons: distances

\[ D_{\gamma} = \frac{1}{n_{IR}\sigma_{pp}} \propto 400 \text{ Mpc} \frac{40 \text{ TeV}}{E} \frac{10nW/(m^2sr)}{(vF(v))_{IR}} \]

\[ \lambda_e = \frac{1}{n_{CMB}\sigma_{ICS}} \sim 1 \text{ kpc} \]

A.Neronov and D.S., astro-ph/0604607
Production of secondary TeV photons: angles and time delay

\[ t_{\text{delay}} = D \delta^2 \frac{\tau - 1}{2\tau^2} \approx 10^5 \text{ years} \]

\[ \tau = n_{\text{IR}} \sigma_{PP} D_{\gamma_0} \]

\[ \delta \leq \Theta_{\text{jet}} \frac{\tau}{\tau - 1} \]

\[ \theta_{ER} = \frac{\delta}{\tau} \]
Production of secondary TeV photons: Energy

\[ E_\gamma = 1.2 \text{ TeV} \left( \frac{E_e}{20 \text{ TeV}} \right)^2 \]
Cascade emission component in the spectra of blazars could be identified and separated from the intrinsic source emission via characteristic

- **spectral** and/or

- **imaging** and/or

- **timing**

properties.
In the absence of measurements of EGMF it is not clear if the observed -ray spectra of blazars emitting in the TeV range are intrinsic to the source or formed in result of development of electromagnetic cascade in the intergalactic space along the line of sight.

If intrinsic source spectrum extends to >10 TeV, cascade emission could contribute in the 0.1-1 TeV band spectrum.
Imaging of cascade: 3-d cascade needed

3-d cascade in turbulent EGMF
A.Neronov, D.Semikoz, M.Kachelriess, S.Ostapchenko and A.Elyev, 2009
**Imaging of cascade: jet opening angle**

- **Imaging**: cascade component forms an extended emission around initially point source.

  - detectability depends on the telescope PSF and on the scale of angular deflections of e+e- pairs
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Evidence of non-zero EGMF in the voids

Neronov & Vovk 2010
If EGMF is negligible, cascade emission component should be commonly present in the spectra of TeV $\gamma$-ray loud blazars.

$$E_\gamma = \varepsilon_{\text{CMB}} \frac{E_e^2}{m_e^2} \approx 0.75 \left( \frac{E_{\gamma 0}}{1 \text{ TeV}} \right)^2 \text{GeV}$$

Electromagnetic cascade emission initiated by TeV photons is peaked in the GeV energy band.
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Electromagnetic cascade emission initiated by TeV photons is peaked in the GeV energy band and can be detected by Fermi!
Could EGMF be B=0?

0.1-0.3 GeV

0.3-1 GeV

1-300 GeV
Fermi upper limits on the steady state flux from high-redshift / hard intrinsic spectra blazars are below the expected level of the cascade emission.
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If the correlation length of EGMF is large, deflection angle is

\[ \delta = \frac{D_e}{R_L} = 2^\circ \left[ \frac{B}{10^{-16} \text{G}} \right] \left[ \frac{E_e}{1 \text{ TeV}} \right]^{-2} \]

If the correlation length of EGMF is small, \( (\lambda_B \ll D_e) \) deflection angle is

\[ \delta = \frac{\sqrt{D_e \lambda_B}}{R_L} = 1^\circ \left[ \frac{B}{10^{-16} \text{G}} \right] \left[ \frac{E_e}{1 \text{ TeV}} \right]^{-3/2} \left[ \frac{\lambda_B}{10 \text{ kpc}} \right]^{1/2} \]
- Strength and spectrum of the cascade component of the spectra is derived assuming a particular EBL spectrum. The bound depends on the (uncertain) normalization of the EBL spectrum.

- GeV and TeV band observations are not simultaneous. The bound depends on the (unknown) variability time scale of the direct source flux.
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The bound has to be verified with dedicated simultaneous GeV-TeV observations of hard-spectra / high-redshift TeV blazars.
Sensitivity of gamma-ray telescopes to “seed” fields
Existing models of the “seed” fields:
- astrophysical seed fields
- cosmological seed fields
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- **astrophysical seed fields**
  - LSS formation: gravitational collapse of proto-galaxies
  - Ejections from the first supernovae
  - Ejections from AGN (100 kpc-scale jets)
  
  No non-negligible magnetic fields outside galaxies/clusters are predicted

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  - Phase transitions in the Early Universe
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Detection of the seed fields with γ-ray telescopes

ULB, May 28, 2010
Detection of the seed fields with $\gamma$-ray telescopes

EGMF-dependent time delay
Detection of the seed fields with $\gamma$-ray telescopes

4C +21.35

PKS 0301-243
Detection of the seed fields with $\gamma$-ray telescopes
Summary

TeV γ-rays from extragalactic sources (blazars) initiate electromagnetic cascades in intergalactic space.

Cascade γ-ray emission is in the GeV band and can be detected by Fermi telescope.

Observational properties of the cascade emission strongly depend on EGMF strength and correlation length.

In the absence of EGMF cascade emission should give contribution into the primary point source flux.

Non-detection of this contribution to the flux of TeV blazars by Fermi rules out the possibility of EGMF with the strength below $\sim 10^{-17} - 10^{-16}$ G.

Evidence for existence of EGMF with the strength above $\sim 10^{-17} - 10^{-16}$ G indicates the seed fields at the origin of magnetic fields in galaxies and galaxy clusters are of cosmological origin.

Future measurement by gamma-ray telescopes will probe EGMF parameter space in the range $10^{-17} - 10^{-12}$ G.