Fermi and intergalactic magnetic fields

Andrii Neronov
ISDC Data Centre for Astrophysics, Geneva

Fermi Symposium, May 11, 2011
Overview

- Gamma-ray induced cascades in the intergalactic space
- Fermi (non) observation of the gamma-ray induced cascade emission
- Implications for intergalactic magnetic fields

Magnetic fields in the Universe

- Problem of the origin of magnetic fields
- Cosmological and astrophysical models of the origin of "seed" fields
- "Seed" magnetic fields in the intergalactic medium
Absorption of Very-High-Energy (VHE) γ-rays in interactions with EBL photons leads to reduction of the source flux in this energy band.

\[\text{e}^+\text{e}^-\text{ pairs produced by the absorbed γ-rays re-emit new γ-rays via inverse Compton scattering of CMB photons.}\]

Secondary Compton emission should be detectable.
**γ-ray induced cascades**

Hard Extragalactic γ-ray source

Extragalactic Background Light (EBL)

TeV γ-rays

$e^+e^-$ pair

Geo γ-rays

observer

AN, Vovk, '10
Tavecchio et al., '10
\textbf{\textit{\gamma-ray induced cascades}}

- Hard Extragalactic \( \gamma \)-ray source
- Extragalactic Background Light (EBL)
- TeV \( \gamma \)-rays
- GeV \( \gamma \)-rays
- \( e^+e^- \) pair
- Observer

\textit{AN, Vovk, '10 Tavecchio et al., '10}

Cascade emission is not detected.
The cascade signal is suppressed.
Fermi and intergalactic magnetic fields

Hard Extragalactic $\gamma$-ray source

Extragalactic Background Light (EBL)

InterGalactic Magnetic Field (IGMF)

TeV $\gamma$-rays

GeV $\gamma$-rays

$e^+e^-$ pair

Cascade emission is not detected.
The cascade signal is suppressed.

AN, Vovk, '10
Tavecchio et al., '10

1ES 0229+200

Fermi
**Fermi and intergalactic magnetic fields**

- **Hard Extragalactic γ-ray source**

- **TeV γ-rays**

- **Extragalactic Background Light (EBL)**

- **InterGalactic Magnetic Field (IGMF)**

- **GeV γ-rays**

- **e⁺e⁻ pair**

- **observer**

**AN, Vovk, '10**

**Tavecchio et al., '10**

**IGMF deviates trajectories of e⁺e⁻ pairs.**

**Secondary γ-rays are emitted away from the line of sight. Cascade flux is suppressed.**

**Fermi non-detection of the cascade flux from hard extragalactic sources implies the existence of non-zero magnetic fields in the intergalactic medium (never detected before).**
Magnetogenesis in the Universe

Galaxies .... 1-10 μG

Galaxy clusters .... 1-10 μG

...... starting from a weak "seed" magnetic field generated before or during Large Scale Structure (LSS) formation

Dynamo compression turbulence

AGN and supernovae outflows

Intergalactic medium ....
Intergalactic "seed" magnetic fields

"Astrophysical" scenario: "Bierman battery" produced by ejections of matter in the intergalactic space by AGN and/or supernovae.

"Cosmological" scenario assume that the same type of mechanism is working at the moments of phase transitions in the Early Universe.
Previously known constraints on IGMF

Magnetic field in the IGM is not stronger than the field in galaxies

Non-observation of Faraday rotation of polarized radio emission from quasars limits possible magnetic fields in IGM

Non-observation of magnetic field induced features in the anisotropy of CMB limits magnetic fields produced before Recombination

Resistive decay removes short-correlation length fields in $T<10$ Gyr

Magnetic field homogeneity scale can, in principle, be comparable to the size of the Universe

AN & Semikoz '09
Lower bound on IGMF from Fermi data

Dermer et al. '10
Taylor, Vovk, AN '10

AN & Vovk '10
Tavecchio et al. '10
Dolag et al. '10
IGMF suppression of the cascade signal

Hard Extragalactic \(\gamma\)-ray source

Extragalactic Background Light (EBL)

InterGalactic Magnetic Field (IGMF)

TeV \(\gamma\)-rays

\(e^+e^-\) pair

GeV \(\gamma\)-rays

observer
Cascade $\gamma$-rays travel along different path than direct $\gamma$-rays from the source.

Cascade signal appears, in general, as extended emission around an initially point source.

Size of the cascade source grows with the increase of $B$. Cascade emission is suppressed as soon as the size of the cascade source is larger than PSF.
Detection of extended emission with Fermi

\[ \Theta \approx \frac{\delta}{\tau_0} = 4^\circ \frac{1}{\tau} \left[ \frac{B}{10^{-16} \text{G}} \right] \left[ \frac{E_\gamma}{1 \text{ GeV}} \right]^{-1} \]

Cascade emission starts to be extended in Fermi when IGMF \( B \geq 10^{-16} \text{ G} \)
Cascade $\gamma$-rays travel along different path than direct $\gamma$-rays from the source.

Cascade signal is, in general, delayed compared to the direct source signal.

Time delay of the cascade emission grows with the increase of $B$. Cascade emission is suppressed as soon as the time delay of the cascade emission is larger than source activity time.
Lower bound on IGMF from Fermi data

Dermer et al. '10
Taylor, Vovk, AN '10

AN & Vovk '10
Tavecchio et al. '10
Dolag et al. '10
Lower bound on IGMF from Fermi data

Ando & Kusenko '10

Takahashi et al. '11
Absorption of TeV gamma-rays from distant blazars and subsequent re-emission of gamma-rays from electromagnetic cascade leads to appearance of extended/delayed gamma-ray emission around extragalactic sources.

Non-detection of cascade emission from TeV blazars by Fermi imposes a lower bound on the intergalactic magnetic field at the level of $\sim 10^{-16}$ G if suppression of the cascade emission is due to extended nature of the cascade source and $\sim 10^{-17}$ G if the suppression is due to the time delay.

If typical IGMF strengths are not far (within an order of magnitude) from the lower bound, extended and/or delayed cascade emission from extragalactic sources will be detected by Fermi.

$\Rightarrow$ Positive detection of cascade emission would provide a measurement of IGMF (rather than just a lower bound).
Ando & Kusenko (2010) claimed a detection of extended emission in the stacked AGN signal.
Verification of the result of Ando & Kusenko (2010) via a direct comparison of photon distribution around AGN with that around Crab pulsar shows that the result of Ando & Kusenko is wrong.
Lower bound on IGMF from Fermi data

Takahashi et al. '11
Bright flare from Mrk 501 was detected during a multiwavelength campaign. Takahashi et al. (2011) claimed that a lower bound on IGMF could be found from non-detection of the flare in the GeV range.
Lower bound on magnetic fields in IGM from Mrk 501 flare data?

Minimal possible cascade flux does not exceed flux level measured by Fermi during the flare.