Gamma-ray emission from non-blazar AGNs

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ICRANet-Armenia
Outline

- Introduction
- Radio Galaxies
- Data analysis
- Spectral and Temporal analysis
- Individual Sources
  - Cen A, Fornax A, 3C 120…. 
- Conclusions
Active Galactic Nuclei
Blazar

- The emission is strongly boosted
- The emission is produced from the compact region in the jet
- Unique possibility to investigate the sub-parsec scale structure of jet

Radio galaxies

- The emission from extended regions comparable with jet emission
- A chance to investigate both the jet and the extended regions
- Investigate the particle acceleration and emission over large scales
Radiogalaxies

- **Morphology:**
  - **Core:** flat spectrum, unresolved
  - **Jets:** up to several 100’s kpc, steeper spectrum, may contain “knots”
  - **Lobes:** big amorphous structure, contain “old” particles
  - **Hot spots:** present in more powerful sources, bright and compact, site of reacceleration
Radiogalaxy types

FR I - BL Lac

FR II - FSRQ

Radio luminosity

$< 10^{41} \text{ erg s}^{-1}$

$> 10^{41} \text{ erg s}^{-1}$

Bulk motion

Low $\Gamma$

High $\Gamma$

Brightness

Toward core

Toward edges

jet

inefficient energy transport

Collimated, efficient energy transport

3C 31 (FR I)

3C 438 (FR II)
Observations in the gamma-ray band can help to understand the particle acceleration and emission processes in the components of radio galaxies.
Fermi LAT - new view

Large Area Telescope (LAT)

KEY FEATURES

• 20 MeV $\rightarrow>$ 300 GeV photon energies

• 2.4 Steradian field of view

• Operated in scanning mode, so views the entire sky every 3 hours.

• Point Source Sensitivity

$$<6 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$$

Gamma-ray Burst Monitor (GBM)

8 keV - 40 MeV
## Third Catalog of AGN

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<th>3LAC Clean Sample (^a)</th>
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### AGN Type

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\(^a\) 1000 3LAC samples.
# Non-Blazar AGNs

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PASS 8

Pass 8 provides a full reprocessing of the entire mission dataset, including an improved event reconstruction, a wider energy range, better energy measurements, and significantly increased effective area.

The accumulation of a larger data set allows detailed temporal analysis in short and long time scales, as well as to study the spectrum with better statistics at energies above several GeV.
Time period: 2008-2015 (7 years)

Allows to study the variability in short and long time scales which allows to investigate the physical processes, such as particle acceleration and emission mechanisms, origin of flares and size, structure and location of the emission.

Energy range: 100 MeV - 300 GeV

The improved statistics allows to investigate the spectrum above GeV energies and test the power-law with exponential cut and broken power-law models. Any cut-off or break in the spectrum will be defined by the cooling of relativistic particles.
## Results

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<td>42.7 ± 2.18</td>
<td>1316</td>
</tr>
<tr>
<td>PKS 1203+04</td>
<td>SSRQ/CSS</td>
<td>2.684 ± 0.1699</td>
<td>8.56 ± 2.51</td>
<td>31.08</td>
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</tbody>
</table>
Spectra
Sources with hard spectrum
The spectrum shows deviation from simple power-law modeling

Power-Law with Exp. cutoff

\[
\frac{dN}{dE} = (9.7 \pm 0.99) \times 10^{-13} \left( \frac{E}{1334} \right)^{-2.17 \pm 0.06} \text{Exp} \left( -\frac{E}{9834} \right) \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}
\]

Log Parabola

\[
\frac{dN}{dE} = (2.67 \pm 0.16) \times 10^{-12} \left( \frac{E}{777.1} \right)^{-2.2 + 0.11 \log(E/777.1)} \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}
\]
The HESS spectrum can be explained when the Power-Law Exponential cut-off model is extrapolated to TeV energies.

\[
\frac{dN}{dE} = (2.5 \pm 0.1) \times 10^{-13} \left( \frac{E}{2382} \right)^{-1.86 \pm 0.04} \text{ cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}
\]

\[
\frac{dN}{dE} = (7.2 \pm 1.32) \times 10^{-11} \left( \frac{E}{100} \right)^{-1.77 \pm 0.06} \exp \left( -\frac{E}{94150} \right) \text{ cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}
\]
Unusual spectrum
Variability

- 3C 275.1
- NGC 6251
- 3C 207

Flux (photons cm$^{-2}$ s$^{-1}$) vs Time (10$^9$)
Variable Sources

3C 380

3C 111
NGC 1275

![Graphs and plots related to NGC 1275, showing data for two different time periods: 2008 Aug 04 - 2015 Aug 04 and 2012 Aug 04 - 2015 Aug 04. The graphs display data in terms of photon counts per square centimeter and time in modified Julian dates.](image-url)
Flare-Post Flare

2009 Feb 01 - 2009 Jul 16

Log_{10} \left[ E dN / dE \right] vs Log_{10}[E(MeV)]

Brown - PowerLaw
Black - PowerLawExpCutoff (index2 = 1)
Green - PowerLawExpCutoff (index2 is free)
Blue - LogParabola

2010 Jun 27 - 2011 Jan 23

Log_{10} \left[ E dN / dE \right] vs Log_{10}[E(MeV)]

Brown - PowerLaw
Black - PowerLawExpCutoff (index2 = 1)
Blue - LogParabola

2013 May 14 - 2014 Mar 25

Log_{10} \left[ E dN / dE \right] vs Log_{10}[E(MeV)]

Brown - PowerLaw
Black - PowerLawExpCutoff (index2 = 1)
Green - PowerLawExpCutoff (index2 is free)
Blue - LogParabola

2014 Oct 22 - 2015 Jun 04

Log_{10} \left[ E dN / dE \right] vs Log_{10}[E(MeV)]

Brown - PowerLaw
Black - PowerLawExpCutoff (index2 = 1)
Green - PowerLawExpCutoff (index2 is free)
Blue - LogParabola
First Flaring period

Index changes from 2.2 to <2.0

Kataoka et al. 2010
More detailed view
GB 1310+487

Gamma-ray/radio-loud narrow-line AGN at $z = 0.638$. 
Flare -1 and Flare -2

Flare -1
2009-11-16—2009-12-21

Flare -2
2010-04-26—2010-07-26

\[
\frac{dN}{dE} = (3.8 \pm 0.2) \times 10^{-11} \left( \frac{E}{1446.36} \right)^{1.8 \pm 0.04} \exp \left( -\left( \frac{E}{23491} \right) \right) \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}
\]

\[
\frac{dN}{dE} = (1.36 \pm 0.12) \times 10^{-11} \left( \frac{E}{1446.36} \right)^{-1.9 \pm 0.02} \exp \left( -\left( \frac{E}{46065} \right) \right) \text{cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}
\]
Luminosity-Photon index
Individual Sources
Fermi LAT data from four years of observations of Cen A => detection of HE (>100 MeV) gamma-rays up to 50 GeV  with detection significance of about 44 sigma

The power-law fit with data:

$$\left( \frac{dN}{dE} \right)_p = (2.73 \pm 0.12) \times 10^{-9} \left( \frac{E}{100 \text{ MeV}} \right)^{-2.69 \pm 0.03}$$

The spectrum shows a tendency for a deviation from a single power law with respect to the data above several GeV.

Broken power-law fit with data:

$$\left( \frac{dN}{dE} \right)_{bp} = (1.19 \pm 0.08) \times 10^{-13} \left( \frac{E}{4 \text{ GeV}} \right)^{-\Gamma_{1,2}}$$

with $\Gamma_1 = 2.74$ and $\Gamma_2 = 2.12$

The log likelihood ratio test givea preference to a broken power-law model.
The results of the data analysis reveal a hardening of the (average) gamma-ray core spectrum toward higher energies. The “unusual” break at 4 GeV could most naturally be explained by a superposition of different spectral components.

The power-law fit in the range 0.1-4 GeV

- Photon index \( \Gamma_1 = 2.74 \pm 0.02 \)
- Flux \( F_\gamma = (1.68 \pm 0.04) \times 10^{-7} \text{ph cm}^{-2} \text{s}^{-1} \)
- Detection significance \( TS = 1944 \)

The power-law fit in the range 4-100 GeV

- Photon index \( \Gamma_2 = 2.09 \pm 0.2 \)
- Flux \( F_\gamma = (4.2 \pm 0.64) \times 10^{-10} \text{ph cm}^{-2} \text{s}^{-1} \)
- Detection significance \( TS = 124.4 \)


hardening of the spectrum!
Time variability

Time variability $\Rightarrow$ region size

$$R \leq \frac{\delta_D}{1+z} ct_{\text{var}} cm$$

Low Energy Component

45 day bin

High Energy Component

90 day bin
For a distance of 3.8 Mpc, corresponds to apparent (isotropic) gamma-ray luminosities:

\[ L_\gamma (0.1 - 4 GeV) \approx 10^{41} \text{ erg s}^{-1} \] and \[ L_\gamma (> 4 GeV) \approx 1.4 \times 10^{40} \text{ erg s}^{-1} \] which are larger than VHE luminosity reported by HESS \[ L_\gamma (> 250 GeV) \approx 2.6 \times 10^{39} \text{ erg s}^{-1} \] Aharonian et al. 2009, ApJ, 695, L40
The lack of significant variability + limited angular resolution (~5 kpc) -> uncertainties production site of the HE gamma-ray emission. In terms of SSC processes occurring in inner jet -> well modeling up to a few GeV (e.g., Chiaberge et al. 2001; Abdo et al. 2010). However the hardening on the HE spectrum above 4 GeV -> appearance of a physically different component.

Different scenarios for new additional component:

(1) non-thermal processes in its BH magnetosphere (Rieger & Aharonian 2009),
(2) multiple SSC-emitting components (i.e., differential beaming; Lenain et al. 2008),
(3) photo-meson interactions of protons in the inner jet (Kachelrieß et al. 2010; Sahu et al. 2012),
(4) gamma-ray-induced pair-cascades in a torus-like region (Roustazadeh & Bottcher 2011),
(5) secondary Compton upscattering of host galaxy starlight (Stawarz et al. 2006),
(6) inverse-Compton processes in the kpc-scale jet (Hardcastle & Croston 2011).

Also gamma-rays can be produced from relativistic protons. Effective gamma-ray production if the diffusion coefficient does not exceed $D \sim R_h^2 / t_{pp} \sim 10^{28}(R_h / 10 \text{kpc})^2 (10^{-2} \text{cm}^{-3} / n) \text{cm}^2 \text{s}^{-1}$ by much. An interesting possibility, especially for the hard HE component with photon index close to 2.1, given the similarity to so-called “Fermi Bubbles”.
Cen A lobes @ HE- 10 month data

After 10 months Fermi LAT operation discovery of the HE gamma-ray emission from radio lobes.

Count map

SED

\[ F_\gamma = 0.77 \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1} \]

\[ F_\gamma = 1.09 \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1} \]

With photon index \( \Gamma \approx 2.6 \)

Gamma-rays are the result of IC scattering of cosmic microwave background photons and the extragalactic background light photons by \textit{in situ accelerated} electrons.

Cen A lobes @ (3 year data)

3 times larger than the previous observation -> study the morphology and photon spectrum with higher statistics.

1) detected >10 sigma up to 6 GeV
2) photon index -2.6 for Southern, harder for Northern -2.24
3) substantial extension of HE emission beyond radio/ WMAP for Northern part
4) HE gives model-independent info about spatial distribution of electrons

The radio luminosity depends on electron density $N_e$ and magnetic-field square $B^2$. The IC gamma-ray luminosity only depends on $N_e$ -> only HE gamma-rays can give model-independent information about both the energy and spatial distribution of electrons.

Extension of HE emission observed for Cen A Northern lobe -> example showing no conclusions can be made about electron density based on radio observations!

**Origin of gamma rays**

**Leptonic origin:**
- radio emission $\Rightarrow$ nonthermal / synchrotron radiation existence of multi-GeV electrons $\Rightarrow$ photons scattering due to IC on different target photon field.
  1. CMB photon field – main contribution
  2. EBL photon field – some contribution (for highest $\gamma$ energies)
  3. Synchrotron photon field – negligible

**Hadronic origin:**
- protons can interact with the ambient low density plasma, creating daughter mesons and neutral component decay into $\gamma$-rays $p + p \Rightarrow \pi^0 \Rightarrow \gamma\gamma$
The general equation describing evolution of energy distribution function $f$ of relativistic particles can be written as

$$\frac{\partial f}{\partial t} = \text{div}(D_r \text{grad } f) - \text{div}(u_r f) + \frac{\partial (P_r f)}{\partial \gamma} - \frac{\partial (b_r f)}{\partial \gamma} + \frac{\partial^2 (d_r f)}{\partial \gamma^2}$$

$P_r$ is the energy loss rate, $D_r$ is the diffusion coefficient, $u_r$ is the fluid velocity and $b_r$ and $d_r$ are acceleration efficiencies. After integration by volume

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial \gamma} (PN) - \frac{N}{\tau_{esc}} + Q$$

where $N(\gamma,t)$ is electron energy distribution function, $\tau_{esc}$ is escape time and $Q(\gamma,t)$ is the injection rate of electrons. The solution of kinetic equation is

$$N(\gamma,t) = \frac{1}{P(\gamma)} \int_{-\infty}^{t} P(\zeta_i) Q(\zeta_i, t_1) e^{-\int_{t_1}^{t} \frac{dx}{\tau(\zeta_x)}} dt_1$$
The particles can escape from the lobes only by diffusion

$$\tau_{esc} = \frac{R^2}{2D(E)}$$

where $D(E)$ is the diffusion coefficient and generally is taken in the form

$$D(E) = \eta \frac{r_g c}{3}$$

$$r_g = 3.3 \times 10^{13} \left( \frac{E}{10 \text{GeV}} \right) \left( \frac{B}{1 \mu \text{G}} \right)^{-1} \text{cm}$$

is the particle gyroradius and $\eta$ is the gyrofactor.

The electrons lose energy mainly by IC cooling

$$t_{cooling} = 1.24 \times 10^8 E^{-1}_{10 \text{GeV}} \text{ yr}$$

the escape distance is

$$t_{cooling} = \tau_{esc} \Rightarrow R = 16.6 B^{-1/2}_{1 \mu \text{G}} \eta^{1/2} \text{ pc}$$

which is very small compared to the size of the outer lobes of Cen A (250 kpc) $\Rightarrow$

$$N(\gamma,t) = \frac{1}{P(\gamma)} \int_{\gamma}^{\xi(t)} Q(\gamma_1) d\gamma_1$$

where $t = \int_{\gamma}^{\xi(t)} \frac{d\gamma_2}{P(\gamma_2)}$ and $P(\gamma)$ is energy loss rate of electrons.
Origin of gamma-rays

Leptonic gamma-rays
Synchrotron emission and IC scattering of electrons for injection $t = 8 \times 10^7$ yr and $\gamma_{\text{max}} = 10^6$. The maximum total energy of leptons

$$W_e = 6 \times 10^{57} \text{erg}$$

Hadronic gamma-rays
For $E_{p_{\text{max}}} = 55 \text{GeV}$ the maximum energy of hadrons

$$W_p = 10^{61} (n/10^{-4} \text{cm}^{-3})^{-1} \text{erg}$$

Fornax A

Distance - 18.6 Mpc
Lobe size - 389 kpc

6.1 years
2008 August 4 - 2014 September 4

Detection significance: \( TS = 121 \approx 11 \sigma \)

The spectrum: \( \Gamma = 2.08 \pm 0.08 \)
Flux: \( (5.34 \pm 0.78) \times 10^{-12} \; \text{erg cm}^{-2} \text{s}^{-1} \)

Ackerman, Ajelo and et al. 2016
Observation in the other waveband

Radio photon index: $\Gamma = 1.68$
X-ray photon index: $\Gamma = 1.62$

The same population of electrons is responsible for radio (synchrotron) and X-ray (IC/CMB) emissions.
IC scattering of EBL photons

Georganopoulos et. al., 2008

The exact measurement of gamma-ray flux will allow to measure the EBL.
The multi-wavelength spectrum allows self-consistent estimation of the parameters describing the particle distribution.

\[ N_e(E_e) = N_0 E_e^{-\alpha} \exp\left( -\left( \frac{E_e}{E_c} \right)^\beta \right) \]

\[ N_e(E_e) = N_0 \begin{cases} E_e^{-\alpha_1} & E_e < E_{br} \\ E_e^{-\alpha_2} & E_e > E_{br} \end{cases} \]

Derive the best-fit and uncertainty distributions of spectral model parameters through Markov Chain Monte Carlo sampling of their likelihood distributions.
\[ N_e(E_e) \propto N_0 E_e^{-\alpha} \exp \left(-\left(\frac{E_e}{E_c}\right)^2\right) \]
The total electron spectrum is formed from the contribution of several relativistic Maxwellian distributions

\[ n(\gamma) = n_0 \gamma^2 e^{-\left(\frac{\gamma}{\gamma_c}\right)^\beta} \]

\[ \gamma_{ci} = (\gamma_1, \gamma_2, \ldots, \gamma_i) \]

\[ W_i \propto \frac{1}{\gamma_{ci}^4} \]
The low energy emission produced from synchrotron emission of electrons, X-ray
Emission from the IC scattering of CMB photons on the same electrons. The
gamma-ray emission produced from the interaction of protons.
Emission from the compact regions

3C 120 radio galaxy at the redshift $z=0.033$ is an active and powerful emitter of radiation at all the observed wavebands.

Large Scale jet up to 100 kpc with several knots.

Harris et al. (2004)
Both the proton synchrotron model and the electron self synchrotron model predict flux detectable by Fermi LAT

Aharonian 2002

Harris et al. 2004
Gamma-ray emission from 3C 120

Fig. 1. Averaged differential spectrum of 3C 120 (above 100 MeV) red points as compared with that based on the initial 15 month data set (Abdo et al. 2010c). The dashed black line shows the power law function determined from the gtlike.

Fig. 2. Gamma-ray light curve from August 4th 2008 to December 4th 2013. The bin size corresponds to 180- (red) and 365-days (blue). The galactic and extragalactic background emission is fixed to the best-fit parameters obtained for the overall time fit.

Based on 5 years of data
New data analysis - flare

Flux (photon cm\(^{-2}\) s\(^{-1}\))

- $10^5$
- $10^6$
- $10^7$
- $10^8$

Time (s)

- 330
- 450

6/21/2016

Sahakyan
Spectrum: flare vs averaged

7-years averaged spectrum

\[ \frac{dN}{dE} = (1.18 \pm 0.14) \times 10^{-12} \left( \frac{E}{1000} \right)^{-2.7 \pm 0.05} \text{ cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \]

**Flare-1**

\[ \left( \frac{dN}{dE} \right)_{\text{APR.24}} = (1.42 \pm 0.19) \times 10^{-10} \left( \frac{E}{1000} \right)^{-2.17 \pm 0.13} \text{ cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \]

**Flare-2**

\[ \left( \frac{dN}{dE} \right)_{\text{SEP.24}} = (5.31 \pm 1.21) \times 10^{-11} \left( \frac{E}{1000} \right)^{-2.26 \pm 0.22} \text{ cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} \]
Origin of gamma-rays

Synchrotron/Synchrotron self-Compton radiation)

Monthly variability - emission region size

\[ R_b \approx 10^{18} \text{ cm} \]

Doppler boosting

\[ \delta = 4 \]

<table>
<thead>
<tr>
<th>( B(\text{mG}) )</th>
<th>( \alpha )</th>
<th>( \gamma_{\text{min}} )</th>
<th>( \gamma_c )</th>
<th>( U_e/U_B )</th>
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<td>( 1.7 \times 10^4 )</td>
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<td>( 9.8 \times 10^3 )</td>
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<td>Dot dashed line</td>
<td>25</td>
<td>2.0</td>
<td>2500</td>
<td>( 1.2 \times 10^4 )</td>
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</table>

The jet luminosity \( L_{\text{jet}} \approx 6 \times 10^{44} \text{ erg s}^{-1} \) which corresponds to 10 % Eddington accretion power.
Another example....

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<th>$B(G)$</th>
<th>$\alpha$</th>
<th>$\nu_{\text{min}}$</th>
<th>$\nu_{c}$</th>
<th>$U_{e}/U_{b}$</th>
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<td>2</td>
<td>200</td>
<td>4500</td>
<td>8</td>
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</tbody>
</table>

$R_{b} \approx 10^{17} \text{ cm}$

$\delta = 4$

3C 111
Conclusions

- The analysis of 7-year of Fermi LAT data from the observations of radio galaxies allows to investigate both the spectrum and variability.
- The spectra of several sources show deviation from a simple power-law modeling (NGC 6251, NGC 1275 etc)
- Strong variation of gamma-ray flux and photon index of NGC 1275 radio galaxy is found.
- The modeling of the emission from extended lobes of Cen A and Fornax A, indicates that the proton contribution can be significant.
- The analysis of simultaneous X-ray data will allow to reconstruct the nonthermal electron spectrum and investigate the particle acceleration/emission in the sub-parsec scale structures of radio galaxies.