Physics of AGN jets in the Fermi era

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Relativistic jets are ubiquitous!

Active galactic nuclei (AGN)  X-ray binaries (XRBs)  Gamma ray bursts (GRBs)

Jet power \( \sim 10^{44} - 10^{48} \text{ erg s}^{-1} \)

Lorentz factor \( \sim 3 - 30 \)

\(~ 10^{38} \text{ erg s}^{-1}~\)

\(~ 3~\)

\(~ 10^{52} \text{ erg s}^{-1}~\)

\(~ 300 - 1000~\)

This talk; see also talks by I. Christie, H. Zhang, E. Meyer & more in AGN sessions

See talks by Wilson-Hodge, H. Zhou & more in Galactic sessions

See talks by A. Beloborodov, B. Zhang, P. Beniamini & more in GRB sessions
Extragalactic γ-ray sky dominated by AGN

9-yr all-sky map

3FGL

~3000 sources
~58% AGN

Blazar contribution to the extragalactic γ-ray background (EGB):
~ 100% at >100 GeV
~ 50% at <100 GeV

Ajello+15, ApJL

Acero+15, ApJS

Credit: NASA/DOE/Fermi LAT Collaboration

~3000 sources
~58% AGN

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~ 100% at >100 GeV
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Ajello+15, ApJL
Highlights from Fermi era
Neutrinos from blazar jets

(e.g. Mannheim '95, Halzen & Zas '97, Atoyan & Dermer '01, Murase+14, Petropoulou+15, Padovani, MP+15, Gao+15)

Production mechanism

Ideal environment for $\nu$ production

- Powerful jets have the potential to accelerate and confine high-energy protons
- Many target photon fields are available (from e.g. jet, BLR, torus, disk)
The multi-messenger flare of TXS 0506+056

- IC 170922A: track event with $E_{\nu} \sim 300$ TeV (ang. res. < 1 deg)
- Automatic public alert via AMON/GCN
- Fermi-LAT reported TXS 0506+056 was in a flaring state (Atel # 10791)
- Many MW observations followed

See talk by A. Franckowiak
Interpretations

Photo-hadronic models

- Ansoldi+18 for MAGIC, ApJL
- Cerruti+18 (1807.04335)
- Gao+18 (1807.04275)
- Keivani, Murase, MP+18, ApJ


Hadro-nuclear models

- He+18 (1808.04330)
- Liu+18 (1807.05113)

More in Keivani’s talk!

$F_{\nu} < 2 \times 10^{-12} \text{ erg/cm}^2/\text{s}$

$U_p/U_e > 300$

$E_{p,max} < 0.3 EeV$
Fermi detects sub-orbital variability from 3C 279

Challenging for standard models because of:

- Minute-scale duration
- High γ-ray luminosity (∼ $10^{49}$ erg s$^{-1}$)
- High Compton ratio ($A_C ∼ 100$)

Ackermann+16, ApJL
Petropoulou+17, MNRAS Letters
Status of blazar modeling

Particle acceleration

Injection of particles

Radiative processes

Photon spectrum

What’s up next?

Build a bottom-up theory for the origin of “blobs”

Test theory predictions against spectro-temporal properties of blazar emission
Energy dissipation in jets

- Internal shocks: time-dependent energy injection to the jet
- Recollimation shocks: abrupt changes in the density of external medium
- Magnetic kink instability at jet interior
- Striped wind structure of jet

(e.g. Romanova & Lovelace ’92, A&A; Eichler’93, ApJ; B

Barniol-Duran+17, MNRAS

Magnetized plasma enters the reconnection region

Plasma leaves the reconnection region at the Alfvén speed

Magnetic energy is transformed to heat, bulk plasma kinetic energy and non-thermal particle energy
Efficient energy dissipation

Radiative power is ~1-10% of jet power

- it transfers ~ 50% of the flow energy (electrons and positrons)
- Efficiency decreases with increasing guide field
Plasmoids in reconnection: the blobs of blazar emission

The layer fragments into plasmoids \cite{loureiro+07, phpl; uzdensky+10, phrvl}

Plasmoids move relativistically in the jet frame \cite[eg. giannios'09, mnras; giannios '13, mnras]{giannios+13, mnras}

Plasmoids have a power-law distribution of sizes \cite[eg. uzdensky+10, phrvl; loureiro+11, mnras]{uzdensky+10, phrvl}

\[ (Sironi, MP, Giannios’ 15; Sironi, Giannios, MP ’16) \]
From microscoPIC to large scales

Self-similarity

Extrapolation to large scales
Variability at multiple scales

Each plasmoid produces a flare of characteristic duration and flux

\[ \Delta t_{1/2} \approx \frac{w_p}{\beta_g c \delta_p} \]

\( \text{Plasmoid size} \)

\( \text{Plasmoid Doppler factor} \)

\[ L_{pk} \approx \frac{f_{rec} L_j}{8 R^2 c \beta_j \Gamma_j^2} \beta_g c w_p^2 \delta_p^4 \]

\( \sigma = 10 \) (FSRQ–like)

Fast flares on top of slowly evolving envelope

Physical model for multi-timescale variability in jets

More in Christie’s talk!
Future prospects

- IXPE: Imaging X-Ray Polarimetry Explorer
- e-ASTROGAM
- KM3NeT
- IceCube
**Fermi** is the only mission that can perform long-term monitoring of blazar jets.

- Timing analysis of light curves
- Flare properties

Synergy of **Fermi** with Cherenkov telescopes delivers high-quality γ-ray spectra extending more than 4 decades in energy.

- Spectral breaks or attenuation features
- Multiple spectral components

**Fermi**’s role in multi-messenger observations of blazar jets is central, as demonstrated by the flare of TXS 0506+056.

- Cosmic-ray content of jets
- Cosmic-ray acceleration in jets

**Fermi** as an integral part in the map of future multi-messenger missions.

Thank you
Back-up slides
The γ-ray spectrum of Centaurus A

- Closest radio galaxy (FR I type)
- D = 3.8 ± 0.1 Mpc \((Harris+10, PASA)\)

\[\text{1-yr Fermi data}\]

\[\text{4-yr Fermi data}\]

\[\text{8-yr Fermi data}\]

\[\text{HESS + Fermi-LAT collaborations (1807.07375)}\]

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SSC modeling of Centaurus A

Cen A as misaligned blazar → SSC modeling of core emission

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SSC</th>
<th>Model (Abdo et al. 2010a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$ (cm)</td>
<td>$4 \times 10^{15}$</td>
<td>$3 \times 10^{15}$</td>
</tr>
<tr>
<td>$B$ (G)</td>
<td>6</td>
<td>6.2</td>
</tr>
<tr>
<td>$\delta$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma_{e,\text{min}}$</td>
<td>$1.3 \times 10^3$</td>
<td>300</td>
</tr>
<tr>
<td>$\gamma_{br}$</td>
<td>–</td>
<td>800</td>
</tr>
<tr>
<td>$\gamma_{e,\text{max}}$</td>
<td>$10^6$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$p_{e,1}$</td>
<td>–</td>
<td>1.8</td>
</tr>
<tr>
<td>$p_{e,2}$</td>
<td>4.3</td>
<td>4.3</td>
</tr>
<tr>
<td>$\ell^\text{inj}$</td>
<td>$6.3 \times 10^{-3}$</td>
<td>$8 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\ell^e$</td>
<td>$4.6 \times 10^{-3}$</td>
<td>$3.7 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Large viewing angle → Weak Doppler boosting

$L_{obs} \propto \delta^4 L_{e,co} \approx L_{e,co}$

$L_{obs \text{ high}} \rightarrow L_{e,co \text{ high}} \rightarrow 2^{nd} \text{ order SSC not negligible!}$


1-yr data

Petropoulou+14, A&A

1-yr data

4-yr data

2^{nd} SSC peak

2^{nd} order ICS in KN regime → steep spectrum
Alternative interpretations

**Inner jet models**

- Leptonic processes in black-hole magnetosphere (Rieger & Aharonian 09, ApJL)
- SSC from 2 zones (Joshi+18, MNRAS Letters; HESS & Fermi Collaborations ‘18)
- Millisecond pulsar population (Brown+17, A&A)
- DM annihilation (Brown+17, A&A)

**Photo-hadronic processes** (Kachelriess+10, PASA; Reynoso+11, A&A; Petropoulou+14, A&A)

**ICS on background photons** (Hardcastle & Croston ‘11, MNRAS)

**Large-scale jet models**

UL of CR proton flux at Earth

Low neutrino flux from core

UL of CR proton flux at Earth
X-rays from large-scale AGN jets

- X-ray emission not an extension of radio
- SSC and IC/CMB (w/o beaming and in equipartition)
How are X-rays being produced?

**IC/CMB model**
(Tavecchio+00, ApJL; Celotti+01, MNRAS)

- Beaming (δ~10) from kpc-scale jet is necessary
- Electron distribution extends to low Lorentz factors (γ~20-200)
- Particles at low energies → increased jet power requirements
- No freedom in GeV flux predictions

**Electron synchrotron models**
(e.g. Harris+04, ApJ; Hardcastle’06, MNRAS)

- Strong beaming is not required
- 2 electron distributions with different energy ranges
  - 2nd electron distribution must begin from high Lorentz factors (γ~10)
  - Less energy-demanding
  - Freedom in GeV flux predictions

**Lepto-hadronic models**

![Graph showing X-ray emission from 3C 273 with IC/CMB and electron synchrotron models](Meyer+15,ApJ)
Fermi rules out the IC/CMB model

- Optical/UV not extension of radio spectrum
- $>2$ spectral components

M84 (knot B)


Electrons

Neutrino properties in a nutshell

Neutrino spectrum depends on:

* Density of target photons
* Energy spectrum of target photons
* Energy spectrum of protons

Typical neutrino energies

Jet photons: \( E_\nu \approx 0.05 E_p \geq 90 P e V \Gamma_1 (\varepsilon_s / 10 \text{ eV})^{-1} \)

BLR photons: \( E_\nu \approx 0.05 E_p \geq 0.9 P e V (\varepsilon_{BLR} / 10 \text{ eV})^{-1} \)

Production efficiency

\[ f_{p\gamma} \propto \frac{L_{ph}}{\varepsilon_{ph} R \delta^3} \propto \frac{L_{ph}}{\varepsilon_{ph} t \delta^4} \]

\[ f_{p\gamma} \propto \frac{L_{BLR}}{\varepsilon_{BLR} R_{BLR}} \]
Effective areas of the analyses

Up-going events
- Larger statistical sample
- Larger effective volume
- Atm. background not removed
- Poorer energy determination

High-energy starting events (HESE)
- Smaller statistical sample
- Smaller effective volume
- Atm. Background removed
- Accurate energy determination

Neutrino Events in IceCube
- Back grounds
  - Cosmic ray induced atmospheric muons
- Main Signal
  - Neutrino induced muons

Up-going events

v_\mu < 1PeV
Major GeV flares

<table>
<thead>
<tr>
<th>No.</th>
<th>T (days)</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$P_{N_{\nu \geq 1}}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flares 1a+1b</td>
<td>105</td>
<td>$0.61 \pm 0.16$</td>
<td>$46 \pm 8$</td>
</tr>
<tr>
<td>Flare 2</td>
<td>70</td>
<td>$0.32 \pm 0.07$</td>
<td>$27 \pm 5$</td>
</tr>
<tr>
<td>Flare 3</td>
<td>98</td>
<td>$0.26 \pm 0.05$</td>
<td>$23 \pm 4$</td>
</tr>
<tr>
<td>Flares 4a+4b</td>
<td>112</td>
<td>$0.26 \pm 0.05$</td>
<td>$23 \pm 4$</td>
</tr>
<tr>
<td>$\Sigma$ Flares</td>
<td>385</td>
<td>$1.46 \pm 0.32$</td>
<td>$77 \pm 7$</td>
</tr>
</tbody>
</table>

Without GeV major flares

<table>
<thead>
<tr>
<th>Season</th>
<th>T (days)</th>
<th>$\nu_\mu + \bar{\nu}_\mu$</th>
<th>$P_{N_{\nu \geq 1}}(%)$†</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/2010-05/2011</td>
<td>364</td>
<td>$0.43 \pm 0.06$</td>
<td>$34 \pm 4$</td>
</tr>
<tr>
<td>06/2011-05/2012</td>
<td>364</td>
<td>$0.38 \pm 0.05$</td>
<td>$32 \pm 3$</td>
</tr>
<tr>
<td>06/2012-05/2013</td>
<td>371</td>
<td>$0.71 \pm 0.11$</td>
<td>$51 \pm 5$</td>
</tr>
<tr>
<td>06/2013-05/2014</td>
<td>341</td>
<td>$0.17 \pm 0.06$</td>
<td>$50 \pm 5$</td>
</tr>
<tr>
<td>06/2014-05/2015</td>
<td>350</td>
<td>$0.47 \pm 0.06$</td>
<td>$38 \pm 4$</td>
</tr>
<tr>
<td>$\Sigma$ w/o Flares</td>
<td>1834a</td>
<td>$2.73 \pm 0.38$</td>
<td>$94 \pm 2$</td>
</tr>
</tbody>
</table>
| $\Sigma$ w Flares    | 1834   | $3.59 \pm 0.60$ | $97 \pm 2$      

* Similar probability for detecting at least 1 neutrino from the 2012 flare alone and
* Still <50%
Constraining the model

Q: What means a neutrino non-detection of Mrk 421?

A: Correlation between >1PeV \( \nu \) and GeV \( \gamma \)-rays differs in major flares

OR

Much lower power is carried by CR in blazar jets

>100 TeV \( \nu \) flux (normalized to \( 4 \times 10^{-10} \) erg/s/cm\(^2\)) vs. \( T \) (yr) needed for IceCube \( \nu \) detection at 90\% (95\%) CL

Upper limits on CR power given a non-detection of muon \( \nu (> 100 \text{ TeV}) \) from Mrk 421 in \( X \) years

\[
\begin{array}{cccccc}
X \ (\text{yr}) & \xi_X \ (90\%) & \xi_X \ (95\%) & \mathcal{L}_{p,X} \ (\text{erg/s}) \ (90\%) & \mathcal{L}_{p,X} \ (\text{erg/s}) \ (95\%) \\
6 & 0.71 & 0.9 & 6.2 \times 10^{47} & 7.8 \times 10^{47} \\
8 & 0.53 & 0.68 & 4.6 \times 10^{47} & 5.9 \times 10^{47} \\
10 & 0.43 & 0.54 & 3.7 \times 10^{47} & 4.7 \times 10^{47} \\
20 & 0.21 & 0.27 & 1.8 \times 10^{47} & 2.3 \times 10^{47}
\end{array}
\]
Relativistic magnetized shocks

Equi-partition between pairs & magnetic field

Sub-luminal shocks

Dissipation efficiency

\[ \cos \theta_1 < \frac{v_1}{c} \]

No particle acceleration for super-luminal shocks (e.g., Kirk & Heaven 1987)

(Sironi & Spitkovsky, 2009, MNRAS)
Particle-in-Cell simulations

- No approximations; full plasma physics of ions and electrons
- Tiny length scales need to be resolved $\rightarrow$ Large & expensive simulations
- Limited time coverage and spatial domains
Plasmoid acceleration

- Acceleration due to tension force of reconnected B-field

- Universal acceleration profile

- Acceleration depends on: size & location

\[
\beta_c \Gamma_c \approx f \left( \frac{X'}{w''} \right) = \sqrt{\sigma} \tanh \left( \frac{\beta_{acc} X' - X'_0}{\sqrt{\sigma} w''} \right)
\]

(Sironi, Giannios, Petropoulou 2016)
Distribution of sizes

Distribution of 4-velocities

Plasmoid distributions

\[ N(\log(w/L)/N_{\text{ref}}) \]

\[ N(|p|/\sigma^{1/2})/N_{\text{ref}} \]

\( \sigma = 3 \)

\( \sigma = 10 \)

\( \sigma = 50 \)

(MP, Christie + 2018, MNRAS)