Modeling AGN Spectral Energy Distributions with Leptonic Models

Justin D. Finke
Space Science Division,
Naval Research Laboratory, Washington, DC, USA

For the Fermi-LAT Collaboration
Outline

• Introduction to modeling
  – Synchrotron/SSC models
  – External Compton models

• Modeling 3C 454.3

• Modeling LAT-detected radio galaxies
  – Cen A
  – M87
  – NGC 1275
The One-Zone Time-Independent SSC Model

\[ \delta_D = [\Gamma (1 - \beta \cos(\theta)) ]^{-1} \]
The One-Zone Time-Independent SSC Model

In blob frame:
- Tangled, homogeneous B-field
- Homogeneous, randomly oriented electron distribution

Radiation is Doppler boosted along our line of sight.

Compton scattering synchrotron photons by the same electrons which produce them

\[ \delta_D = \left[ \Gamma \left( 1 - \beta \cos(\theta) \right) \right]^{-1} \]
The One-Zone Time-Independent SSC Model

In blob frame:
- Tangled, homogeneous B-field
- Homogenous, randomly oriented electron distribution

Radiation is Doppler boosted along our line of sight.

Compton scattering synchrotron photons by the same electrons which produce them.

Write SSC as a function of:
\[ \delta_{D}, B, R_{b}', N_{e}(\gamma). \]

Can constrain \( R_{b}' \) based on observations:
\[ R_{b}' \leq \frac{\delta_{D} c t_{\text{var}}}{(1 + z)} \]

Can constrain \( N_{e}(\gamma) \) by relating synch. power-law to electron power-law.
Synchrotron/SSC Model

If scattering is in the Thomson regime, one can derive simple analytic approximations:

\[
\delta_D \approx 5.3 \left( \frac{\nu_{SSC,25}}{t_d \nu_{syn,16}^2} \right)^{1/2} \left( \frac{A(\alpha_1, \alpha_2) L_{SSC,45}^2}{L_{syn,45}} \right)^{1/4}
\]

\[
B \approx 0.68 G (1+z) \frac{\nu_{syn,16}^3 t_d^{1/2}}{\nu_{SSC,25}^{3/2}} \left( \frac{L_{SSC,45}}{A(\alpha_1, \alpha_2) L_{syn,45}^2} \right)^{1/4}
\]

\[
A(\alpha_1, \alpha_2) = (\alpha_1 - 1)^{-1} + (1 - \alpha_2)^{-1}
\]

Ghisellini et al. (1996); Tavecchio et al. (1998)

Can observe dependences on observable parameters.
Synchrotron/SSC Model

Used BL Lac SEDs from Abdo et al. (2010), ApJ, 716, 30

RG SEDs from dedicated papers:


Parameters for NGC 1275 not right, probably longer variability timescale.
Thomson and Compton cross-sections

Dashed: Thomson + cutoff
Solid: Compton

Full Compton expression from Jones (1968).

Full Compton expression needed to accurately represent SSC spectrum.

\[ \delta_D = 100, \quad B = 10 \text{ mG}, \quad t_v = 300 \text{ s} \]

Finke, Dermer, & Böttcher (2008)
Internal $\gamma\gamma$ absorption

$\gamma \rightarrow e^- e^+$

Leads to constraint on Doppler factor:

$$\delta_D \geq \left[ \frac{2^{\alpha}(1+z)^{2\alpha} \sigma T D^2}{m_e c^4 t_v,\text{min}} \epsilon_{\gamma} f_{\epsilon_{\gamma}^{-1}} \right]^{\frac{1}{4+2\alpha}}$$

where $\alpha = \alpha_1$ for

$$\epsilon_{\gamma}^{-1} < \frac{(1+z)^2 \epsilon_{pk}^{\text{syn}}}{2\delta D}$$

and $\alpha = \alpha_2$ for

$$\epsilon_{\gamma}^{-1} > \frac{(1+z)^2 \epsilon_{pk}^{\text{syn}}}{2\delta D}$$

Using synch/SSC expressions:

$$\delta_D \geq 4.4 \left[ 2^{-\alpha}(1+z)^{2\alpha} \epsilon_{\gamma,7} D_{25} f_{\epsilon_{\gamma}^{-1},-10} \epsilon_{pk,7}^{\text{syn}} \sqrt{f_{pk,10}^{\text{SSC}}} \frac{1}{\sqrt{A(\alpha_1, \alpha_2)}} \right]^{1/4}$$

e.g., Dondi & Ghisellini (1995), MNRAS, 273, 583; Ackerman et al. (2010), arXiv:1005.2141
Various radiation components can Compton scatter and absorb $\gamma$-rays. Likely found in FSRQs.

Various radiation components can Compton scatter and absorb γ-rays. Likely found in FSRQs.

External Sources for Compton Scattering and $\gamma\gamma$ Absorption

Various radiation components can Compton scatter and absorb $\gamma$-rays. Likely found in FSRQs.

The Quasar
Fermi-LAT Spectrum of the FSRQ 3C 454.3

- Data taken from July -- October 2008
- Exhibits spectral break:
  - $\Gamma_1 = 2.3 \pm 0.1$
  - $\Gamma_2 = 3.5 \pm 0.25$
  - $E_{\text{brk}} = 2.4$ GeV
- Variable on timescales ~ few days
- Optical (SMARTS, Swift-UVOT), $\gamma$-rays (Fermi-LAT) have well-correlated variability while X-rays (Swift-XRT) do not (Bonning et al. 2009, ApJ, 697, L81).
The 3C 454.3 SED

- Optical & X-ray constrain $p_1 \sim 1.8$, $p_2 \sim 4.8$ ($n_e \sim \gamma^{-p}$).

- Approximately consistent with synchrotron & Compton scattering in fast cooling regime.

- This is not consistent with the LAT spectrum spectral indices if this component is from Compton scattering of a single photon source.

LAT spectrum could be explained by:
- broad Compton scattering component
- Compton scattering of multiple photon sources.
SSC Model Fit

- synch/SSC fit explains SED ok but problems:
  - Doesn’t fit $\gamma$-rays so great.
  - Ignores BLR which must be present due to optical spectrum.
  - Far from equipartition.
  - $B / B_{eq} = 0.06$

Model Fit

- Combination of EC-disk (lower energy) and EC-BLR (higher energy) fits well.

- This model:
  - Agrees with all observations including variability.
  - Includes BLR.
  - Close to equipartition.
  - $B / B_{eq} = 0.6$

Model Fit

- Combination of EC-disk (lower energy) and EC-BLR (higher energy) fits well.

- This model:
  - Agrees with all observations including variability.
  - Includes BLR.
  - Close to equipartition.
  - $B / B_{eq} = 0.6$

IC-disk and IC-BLR model

- BLR $e^-$ number density $\sim r^{-2}$ gives $u_{BLR} \sim r^{-3}$, similar to $u_{disk}$.
- For this combination to explain break, $u_{disk} \sim u_{BLR}$.
- The spectral break will exist independent of $r$.
- Requires $\tau_{BLR} \sim R_g/R_{BLR,i}$
- Can spectral breaks in other sources be attributed to this model? Could breaks be from internal $\gamma\gamma$ absorption (e.g., Reimer 2007)?

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Multi-component Model</th>
<th>SSC Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>0.859</td>
<td>0.859</td>
</tr>
<tr>
<td>$\Gamma_{\text{bulk}}$</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$\delta_\text{D}$</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>$B$</td>
<td>0.4 G</td>
<td>0.032 G</td>
</tr>
<tr>
<td>$t_v$</td>
<td>$1.7 \times 10^5$ s</td>
<td>$1.7 \times 10^5$ s</td>
</tr>
<tr>
<td>$p_1$</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>$p_2$</td>
<td>4.4</td>
<td>4.8</td>
</tr>
<tr>
<td>$\gamma'_{\text{min}}$</td>
<td>$3 \times 10^1$</td>
<td>10</td>
</tr>
<tr>
<td>$\gamma'_{\text{max}}$</td>
<td>$2 \times 10^4$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>$\gamma'_{\text{brk}}$</td>
<td>$1.1 \times 10^3$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$M_0$</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>$l_{\text{Edd}}$</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>1/12</td>
<td></td>
</tr>
<tr>
<td>$r$</td>
<td>$1.5 \times 10^3 R_g$</td>
<td></td>
</tr>
<tr>
<td>$\tau_{\text{BLR}}$</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>$R_i$</td>
<td>$5.0 \times 10^2 R_g$</td>
<td></td>
</tr>
<tr>
<td>$R_o$</td>
<td>$5.0 \times 10^5 R_g$</td>
<td></td>
</tr>
<tr>
<td>$\zeta$</td>
<td>$-2$</td>
<td></td>
</tr>
<tr>
<td>$B/B_{\text{eq}}$</td>
<td>0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>$P_{j,B}$</td>
<td>$1.8 \times 10^{45}$ erg s$^{-1}$</td>
<td>$10^{43}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>$P_{j,\text{par}}$</td>
<td>$2.7 \times 10^{46}$ erg s$^{-1}$</td>
<td>$2.3 \times 10^{47}$ erg s$^{-1}$</td>
</tr>
</tbody>
</table>

Radio Galaxies
Jet emission from radio galaxies

• The viewing angle gives a significant constraint for radio galaxies (Urry & Padovani 1995; Abdo et al. 2010, submitted):

\[ \delta_D \leq \csc \theta_j \]

• So Doppler factors (and hence Lorentz factors) must be small for off-axis RG emission.

• Modeling SEDs of radio galaxies gives typically lower \( \delta_D \) than blazars.

• But they are still brighter than one would expect from de-beamed blazar emission.

— Does this imply that RG emission is from a slower region than blazars (e.g., Chiaberge 2000)?
Cen A

- An FR I radio galaxy 3.7 Mpc from Earth

- Has been detected with EGRET (Hartman 1999) and HESS (Aharonian et al. 2009).

- Giant (10 deg) radio lobes, detected in $\gamma$-rays by the LAT (Abdo et al. 2010, Science, 328, 725; Cheung, Wed.)

- LAT core spectrum is consistent with EGRET.

- The LAT, HESS and EGRET showed no evidence for variability.

- From radio observations, $\theta_j \geq 15$ deg (Hardcastle et al. 2003).
Cen A $\gamma$-ray Spectrum

Non-simultaneous HESS spectrum from 2008

If HESS spectrum is scaled down by its normalization uncertainty, it is barely consistent with extrapolated LAT spectrum.

Neither LAT nor HESS show any variability.

Statistical-only errors
Statistical + systematic errors

Cen A SED

Red: simultaneous
Black: archival

Photoabsorption implies SSC cannot explain LAT and HESS $\gamma$-rays.

Cen A SED

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_j$</td>
<td>7.0</td>
</tr>
<tr>
<td>$\delta_D$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\theta_j$</td>
<td>30 deg</td>
</tr>
<tr>
<td>B</td>
<td>6.2 G</td>
</tr>
<tr>
<td>$t_{\text{var}}$</td>
<td>$1.0 \times 10^5$ s</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$3.0 \times 10^{15}$ cm</td>
</tr>
<tr>
<td>$p_1$</td>
<td>1.8</td>
</tr>
<tr>
<td>$p_2$</td>
<td>4.3</td>
</tr>
<tr>
<td>$\gamma_{\min}$</td>
<td>$3 \times 10^2$</td>
</tr>
<tr>
<td>$\gamma_{\max}$</td>
<td>$1 \times 10^8$</td>
</tr>
<tr>
<td>$\gamma_{\text{brk}}$</td>
<td>$8 \times 10^2$</td>
</tr>
<tr>
<td>$P_{j,B}$</td>
<td>$6.5 \times 10^{43}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>$P_{j,e}$</td>
<td>$3.1 \times 10^{43}$ erg s$^{-1}$</td>
</tr>
</tbody>
</table>

Cen A SED

\[ \Gamma_j = 7.0 \]
\[ \delta_D = 1.0 \]
\[ \theta_j = 30 \text{ deg} \]
\[ B = 6.2 \text{ G} \]
\[ t_{\text{var}} = 1.0 \times 10^5 \text{ s} \]
\[ R_b = 3.0 \times 10^{15} \text{ cm} \]
\[ p_1 = 1.8 \]
\[ p_2 = 4.3 \]
\[ \gamma_{\text{min}} = 3 \times 10^2 \]
\[ \gamma_{\text{max}} = 1 \times 10^8 \]
\[ \gamma_{\text{brk}} = 8 \times 10^2 \]
\[ P_{j,B} = 6.5 \times 10^{43} \text{ erg s}^{-1} \]
\[ P_{j,e} = 3.1 \times 10^{43} \text{ erg s}^{-1} \]

Size scale limited by TANAMI observations (Mueller, Ojha, Kadler, Ploetz, Hase). Talk by Ojha Tuesday, poster P18 by Mueller.

The Radio Galaxy
M 87
M87

- FRI at $D = 16$ Mpc

- Regular detections by TeV telescopes (e.g., Aharonian 2006, Acciari 2008, 2009). Some controversy over origin of TeV $\gamma$-rays, whether from core or farther out (HST-1).

- Angle $\theta_j < 19$ deg (Biretta et al. 1999, ApJ, 520, 621). Smaller angles than Cen A means larger $\delta_D$, and $\gamma\gamma$ absorption constraint can be avoided.

- No LAT variability in 10 month data. LAT spectrum consistent with EGRET.
M87

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_j$</td>
<td>2.3</td>
</tr>
<tr>
<td>$\delta_D$</td>
<td>3.9</td>
</tr>
<tr>
<td>$\theta_j$</td>
<td>10 deg</td>
</tr>
<tr>
<td>$B$</td>
<td>0.055 G</td>
</tr>
<tr>
<td>$t_{\text{var}}$</td>
<td>$1.2 \times 10^5$ s</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$1.4 \times 10^{16}$ cm</td>
</tr>
<tr>
<td>$p_1$</td>
<td>1.6</td>
</tr>
<tr>
<td>$p_2$</td>
<td>3.6</td>
</tr>
<tr>
<td>$\gamma_{\text{min}}$</td>
<td>1</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}$</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td>$\gamma_{\text{brk}}$</td>
<td>$4 \times 10^3$</td>
</tr>
<tr>
<td>$P_{j,B}$</td>
<td>$2.0 \times 10^{40}$ erg s$^{-1}$</td>
</tr>
<tr>
<td>$P_{j,e}$</td>
<td>$7.0 \times 10^{42}$ erg s$^{-1}$</td>
</tr>
</tbody>
</table>

TeV from a non-simultaneous low state

The Radio Galaxy
NGC 1275
NGC 1275

- Per A, 3C 84
- $z = 0.018 \ (d_L = 75 \text{ Mpc})$
- Seyfert 1.5 (Veron-Cetty & Veron 2006)
- In initial LAT detection (4 months of data), it was unclear location of $\gamma$-rays, whether from Perseus Cluster or Per A (Abdo et al. 2009, ApJ, 699, 31), and no $\gamma$-ray variability found.
- With additional 8 months of data, Per A origin and variability on month timescales was found (Kataoka et al. 2010, ApJ, 715, 554).
NGC 1275

Original modeling used large var. time, consistent with obs. at that time.

NGC 1275

- Using $t_{\text{var}} = 1$ month, Thomson limit equations give $B = 0.016 \text{ G}$ and $\delta_D = 8.6$. This implies $\theta_j < 6.6 \text{ deg}$.

- Radio morphology, location of the core, somewhat ambiguous (e.g., Vermeulen et al. 1994; Nesterov et al. 1995; Walker et al. 2000; Nagai et al. 2010)

- Also see talks on Wednesday, by Hiroshi Nagai & Kenneth Kellerman.

8.4 GHz.
Radio Galaxy Modeling Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Cen A</th>
<th>M87</th>
<th>NGC 1275</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Lorentz Factor</td>
<td>$\Gamma_j$</td>
<td>7.0</td>
<td>2.3</td>
<td>1.8</td>
</tr>
<tr>
<td>Doppler Factor</td>
<td>$\delta_D$</td>
<td>1.0</td>
<td>3.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Jet Angle</td>
<td>$\theta_j$</td>
<td>30°</td>
<td>10°</td>
<td>25°</td>
</tr>
<tr>
<td>Magnetic Field [G]</td>
<td>$B$</td>
<td>6.2</td>
<td>0.055</td>
<td>0.05</td>
</tr>
<tr>
<td>Variability Timescale [sec]</td>
<td>$t_v$</td>
<td>$1.0 \times 10^5$</td>
<td>$1.2 \times 10^5$</td>
<td>$3.0 \times 10^7$</td>
</tr>
<tr>
<td>Comoving blob size scale [cm]</td>
<td>$R_b'$</td>
<td>$3.0 \times 10^{15}$</td>
<td>$1.4 \times 10^{16}$</td>
<td>$2.0 \times 10^{18}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Cen A</th>
<th>M87</th>
<th>NGC 1275</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-Energy Electron Spectral Index</td>
<td>$p_1$</td>
<td>1.8</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>High-Energy Electron Spectral Index</td>
<td>$p_2$</td>
<td>4.3</td>
<td>3.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Minimum Electron Lorentz Factor</td>
<td>$\gamma_{min}$</td>
<td>$3 \times 10^2$</td>
<td>1.0</td>
<td>$8.0 \times 10^2$</td>
</tr>
<tr>
<td>Maximum Electron Lorentz Factor</td>
<td>$\gamma_{max}$</td>
<td>$1 \times 10^8$</td>
<td>$1.0 \times 10^7$</td>
<td>$4.0 \times 10^5$</td>
</tr>
<tr>
<td>Break Electron Lorentz Factor</td>
<td>$\gamma_{brk}$</td>
<td>$8 \times 10^2$</td>
<td>$4 \times 10^3$</td>
<td>$9.6 \times 10^2$</td>
</tr>
<tr>
<td>Jet Power in Magnetic Field [erg s$^{-1}$]</td>
<td>$P_{j,B}$</td>
<td>$6.5 \times 10^{43}$</td>
<td>$2.0 \times 10^{40}$</td>
<td>$2.3 \times 10^{44}$</td>
</tr>
<tr>
<td>Jet Power in Electrons [erg s$^{-1}$]</td>
<td>$P_{j,e}$</td>
<td>$3.1 \times 10^{43}$</td>
<td>$7.0 \times 10^{42}$</td>
<td>$2.3 \times 10^{43}$</td>
</tr>
</tbody>
</table>

$L_{edd} = 1.2 \times 10^{47} \text{ M}_9 \text{ erg s}^{-1}$
Synchrotron/SSC Model

How accurate are approximate expressions?

NGC 1275 used different variability time
Blazar Unification

Are radio galaxies populating a new region of this plot? Evidence for emission from a different region region of the jet?

The cores of RGs are brighter than one would expect from de-beamed BL Lacs (Chiaberge et al. 2000). Explained by slower flow in sheath or slower flow closer to jet (Georganopoulos & Kazanas 2003).

Is NGC 1275 a blazar?

Summary

- **3C 454.3**
  - SED and $\gamma$-ray spectrum can be modeled as a combination of EC components, including wind BLR.

- **Cen A**
  - Synch/SSC can explain all emission except non-simultaneous TeV HESS emission.

- **M87**
  - Synch SSC can explain all emission including non-simultaneous low state HESS emission.

- **NGC 1275 / Per A**
  - Synch/SSC can only explain latest emission if angle to line of sight is small ($\sim 7$ deg).
Backup Slides
Blazar SED

- Synchrotron scattering
- Compton scattering

$\nu F_\nu$
Blazar SED

Compton scattering of:
- synchrotron (SSC)
- disk radiation
- broad line regions
- torus radiation
- slow sheath surrounding blob  
  (Ghisellini et al. 2005)
Blazar Sequence

- Flat Spectrum Radio Quasar
- Low-peaked BL Lac
- High-peaked BL Lac

νF_ν vs ν

- Radio
- Optical
- X-rays
- Fermi LAT γ-rays
- ACT γ-rays

Unified Model of AGN

Active Galactic Nucleus (~$10^{6-9}$ solar mass black hole)

Spiral → Active Galactic Nucleus → Elliptical
Unified Model of AGN

Active Galactic Nucleus (~10^6-9 solar mass black hole)

- **Spiral**
  - Highly-ioned emission lines
  - Broad emission lines?
    - yes: Sy 1
    - no: Sy 2
  - Lowly-ioned emission lines
  - Broad emission lines?
    - yes: LINER 1
    - no: LINER 2

- **Elliptical**
Unified Model of AGN

Active Galactic Nucleus (~$10^{6-9}$ solar mass black hole)

- Spiral
  - Highly-ioned emission lines
    - Broad emission lines?
      - yes: Sy 1
      - no: Sy 2
  - Lowly-ioned emission lines
    - Broad emission lines?
      - yes: LINER 1
      - no: LINER 2

- Elliptical
  - Radio loud?
    - yes: Radio Galaxy
    - no (90% of AGN): Radio Quiet Quasar
Unified Model of AGN

Active Galactic Nucleus (~10^6-9 solar mass black hole)

- Spiral
- Elliptical

Highly-ionized emission lines

Broad emission lines?
- Yes → Sy 1
- No → Sy 2

Sy 1
- Yes → Radio Quiet Quasar
- No → Radio Galaxy

Sy 2
- Yes → LINER 1
- No → LINER 2

Radio loud?
- No (90% of AGN)
- Yes → Radio Galaxy

Large angle to line of sight
- Yes → FR I
- Small opening angle → FR II
Unified Model of AGN

Active Galactic Nucleus (~10^6-9 solar mass black hole)

Spiral

Elliptical

Highly-ioned emission lines

Broad emission lines?

yes

Sy 1

no

Sy 2

Radio Quiet

Quasar

Yes

Radio loud?

No
(90% of AGN)

Radio Galaxy

Small angle to line of sight

~1% of radio galaxies

Blazar

Strong emission lines?

Large angle to line of sight

FR I

Large opening angle

FSRQ

yes

BL Lac Object

Small opening angle

no

FR II
Radio Loud AGN

Fanaroff-Riley I

3C 31

Plume
Jet
Plume

3C 98

Jet
Hotspot
Lobe

Fanaroff-Riley II

Urry & Padovani (1995)
Radio Loud AGN

Fanaroff-Riley I: Low power, wide opening angle. Jet pointed away from us.

Fanaroff-Riley II: High power, narrow angle. Jet pointed towards us.

3C 31

3C 98

Urry & Padovani (1995)

FR I: Jet pointed away from us.

FR II: Jet pointed towards us.

BL Lac: FSRQ
Radio Loud AGN

Evidence:

Diffuse radio lobes in BL Lacs

Statistics of blazars

Apparent Superluminal motion

Low power, wide opening angle

High power, narrow angle

Jet pointed away from us

Jet pointed towards us

FR I

FR II

BL Lac

FSRQ

3C 98

3C 31

Urry & Padovani (1995)
Beaming Physics

Rest Frame

e.g., Rybicki & Lightman (1979)
Beaming Physics

Rest Frame

\( \Gamma = (1 - \beta^2)^{-1/2} \)

e.g., Rybicki & Lightman (1979)
Beaming Physics

\[ \Gamma = (1 - \beta^2)^{-1/2} \]

\[ \theta_{\text{jet}} = 1/\Gamma \]

e.g., Rybicki & Lightman (1979)
Beaming Physics

\[ \Gamma = (1 - \beta^2)^{-1/2} \]

\[ \theta_{\text{jet}} = 1/\Gamma \]

\[ e.g., \text{Rybicki & Lightman (1979)} \]
Beaming Physics

\[ \Gamma = (1 - \beta^2)^{-1/2} \]

\[ \theta_{\text{jet}} = 1/\Gamma \]

Radio galaxy statistics imply that on average, \( \Gamma \sim 15 (\beta \sim 0.998) \)

e.g., Rybicki & Lightman (1979)

\( \theta_{\text{jet}} \)
Modeling Blazars: electron distribution

Electron distribution:

\[ n_e(\gamma) \sim \gamma^{-p} \]
Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.

Electron distribution:

\[ n_e(\gamma) \sim \gamma^{-p} \]
Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.

Electrons radiative energy by synchrotron and Compton processes. $d\gamma/dt \sim \gamma^3 n_e(\gamma)$
Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.

Electrons radiative energy by synchrotron and Compton processes. $d\gamma/dt \sim \gamma^3 n_e(\gamma)$

Electron distribution: $n_e(\gamma) \sim \gamma^{-p}$
Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.

Electrons radiative energy by synchrotron and Compton processes. $d\gamma/dt \sim \gamma^3 n_e(\gamma)$

Electron distribution: $n_e(\gamma) \sim \gamma^{-p}$
Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.

Electrons radiative energy by synchrotron and Compton processes. \( \frac{d \gamma}{dt} \sim \gamma^3 n_e(\gamma) \)

Electron distribution: \( n_e(\gamma) \sim \gamma^{-p} \)
Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.

Electrons radiative energy by synchrotron and Compton processes. \( d\gamma/dt \sim \gamma^3 n_e(\gamma) \)

Electron distribution:
\( n_e(\gamma) \sim \gamma^{-p} \)

Synchrotron/Compton cooling break:
\( \Delta p = 1 \)
Blazar Unification

Are radio galaxies populating a new region of this plot?

Or is there a selection effect?

The cores of RGs are brighter than one would expect from de-beamed BL Lacs (Chiaberge et al. 2000). Explained by slower flow in sheath or slower flow closer to jet (Georganopoulos & Kazanas 2003).

LBAS blazars with RGs.