AGN physics in the age of Fermi

Fermi Summer School
Lewes, DE, 13-17 September, 2010

Chuck Dermer
United States Naval Research Laboratory
Washington, DC USA
charles.dermer@nrl.navy.mil

On behalf of the Fermi Collaboration

Outline
1. Radio Galaxies, Blazars, and Unification
2. Blazar Sequence
3. SED: Two Component Paradigm
4. Jet Physics: $\gamma\gamma$ opacity and synchrotron/SSC model
5. External Compton scattering processes
6. Variability
Blazar 3C 454.3’s Record Flare

November 3, 2009
Fermi AGNs

- LAT Bright AGN Sample (LBAS); First year LAT AGN Catalog (1LAC)

**3EG (EGRET):**
10 \(>10\sigma\) \(|b|>10^\circ\) sources
66 \(>5\sigma\) blazars

**LBAS:** subset of 0FGL w/ 205 sources
TS \(>100\) \((>10\sigma)\)
106 \(|b|>10^\circ\) sources
assoc. w/ AGNs

**1FGL TS >25**
1451 sources
1043 \(|b|>10^\circ\) sources

**1LAC**
TS \(>25\) \((>4.1\sigma)\)
671 assoc. w/ 709 AGN
(663 hi-conf. associations)
(300 BL Lacs, 296 FSRQ, 41 other AGN, 72 unknown)

**2FGL TS >25**
1888 sources
832 AGNs (+268 candidates)
114 Pulsars
60 SNR/PWNes
593 unaccounted
7 others

**2LAC**
360 FSRQs
420 BL Lacs (~60% with known z)
200 of unknown type
~20 other AGN
Classifying Fermi AGNs

- **Radio:** FR1 vs FR2
- **Optical:** FSRQs vs. BL Lacs
- **SED;** (“synchrotron-peaked”)
  - LSP ($\nu_{pk}^{syn} < 10^{14}$ Hz)
  - HSP ($\nu_{pk}^{syn} > 10^{15}$ Hz)
- ISP

Essentially all FSRQs are LSPs

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![Graphs showing classification of Fermi AGNs](image)
AGN Unification Paradigm

(Urry and Padovani 1995)
γ-Ray Galaxy Luminosity

Fermi blazar divide
(Ghisellini et al. 2009)

Misaligned AGNs
(host galaxies of blazars)

Star forming galaxies
Spectral Index Distribution
Blazar Sequence

- Searching for the Hertzsprung-Russell Diagram in blazar studies
- Inverse correlation between $E_{\text{peak}}$ and luminosity
- Cooling model with external radiation for FSRQs (Ghisellini et al. 1998)
- Selection biases from 2 Jy FSRQs (Wall & Peacock catalog), 1 Jy BL Lac (radio selected), and Einstein Slew Survey (X-ray selected) (Giommi et al. 1999; Padovani et al. 2003, Padovani 2007)
Understanding the Blazar Sequence

- Inverse correlation between $E_{\text{peak}}$ and luminosity (Fossati et al. 1998)
- Cooling model with external radiation for FSRQs (Ghisellini et al. 1998)
- Origin of the sequence
  - Galaxy evolution through reduction of fuel from surrounding gas and dust (Böttcher and Dermer 2002)
  - BZ effect (Cavaliere and d'Elia 2002)

RLNL Sy 1s
PMN J0948+0022
z=0.585

Spectral Energy Distributions of Blazars: Two Component Paradigm

Mrk 501, z = 0.033
PG 1553+113, z < 0.75
HST: z~0.40-0.43

3C 279, z = 0.538


Mrk 421, z = 0.031

3C 454.3, z = 0.859


PG 1553+113, z < 0.75
HST: z~0.40-0.43

3C 279, z = 0.538

Blazar Modeling

Nonthermal $\gamma$ rays $\Rightarrow$ relativistic particles + intense photon fields

**Leptonic jet model:**
Nonthermal synchrotron paradigm
Associated SSC and EC component(s)
Location of emission site

**Hadronic jet model:**
Secondary nuclear production
\[ pN \rightarrow \pi^0, \pi^\pm \rightarrow \gamma, \nu, n, e^\pm \]
Proton and ion synchrotron radiation
\[ pB \rightarrow \gamma \]
Photomeson production
\[ p\gamma \rightarrow \pi^0, \pi^\pm \rightarrow \gamma, \nu, n, e^\pm \]
High energy $\gamma$-ray component from $\gamma\gamma'$ $\rightarrow$ $e^\pm$ $\rightarrow$ $\gamma$ by Compton or synchrotron processes
Neutrons escape to become UHECRs
Synchrotron/Compton
Leptonic Jet Model

BL Lac vs. FSRQs
Target photons for scattering
Accretion regime

Blob Formalism

Energy Sources:
1. Accretion Power
2. Rotation Power

Supermassive Black Holes
Identifying hadronic emissions
Doppler Factor

\[ \delta_D \equiv [\Gamma (1 - \beta \cos \theta)]^{-1} \]

\[ \Delta x = \beta c \Delta t_* = \beta \Gamma c \Delta t' \]

\[ t = t_* + \frac{d}{c} - \frac{x \cos \theta}{c} \]

\[ t + \Delta t = t_* + \Delta t_* + \frac{d}{c} - \frac{(x + \Delta x) \cos \theta}{c} \]

\[ \Rightarrow \Delta t = \frac{\Delta x}{\beta c} (1 - \beta \cos \theta) = \Gamma \Delta t'(1 - \beta \cos \theta) \]

\[ \Rightarrow \Delta t = \frac{\Delta t'}{\delta_D} \quad \theta = 0 \Rightarrow \Delta t = \frac{\Delta x}{\beta c} (1 - \beta) = \frac{\Delta x}{\Gamma^2 c} \]

\[ dt = \frac{(1 + z) dt'}{\delta_D} \]

\[ \varepsilon = \frac{\delta_D \varepsilon'}{(1 + z)} \]
Variability and Source Size

Source size from direct observations:

\[ r'_b \equiv d_A \vartheta = 2\left( \frac{d_A}{10^{27} \text{ cm}} \right) \vartheta(\text{mas}) \, \mu \text{c} \]

Source size from temporal variability:

\[ r'_b \lesssim c t'_\text{var} = c \delta_D t_{\text{var}} / (1 + z) \]

\[ r'_b (\text{cm}) < \frac{2.5 \times 10^{15} \delta_D t_{\text{var}} (\text{day})}{(1 + z)} \]

Variability timescale implies maximum emission region size scale
Variability and Source Location

\[ c\Delta t/(1+z) \approx x(1 - \cos \theta) \approx x\theta^2/2 \approx x/2\Gamma^2 \]
\[ \Rightarrow x \approx 2\Gamma^2 c\Delta t/(1+z) \]

\[ R_s = \frac{2GM}{c^2} < \frac{ct_{\text{var}}}{(1+z)} \]

Variability timescale implies engine size scale, comoving size scale factor \(\approx \Gamma\) larger and emission location \(\sim \Gamma^2\) larger than values inferred for stationary region.

Rapid variability by energizing regions within the Doppler cone.
Energy Fluxes, Blobs and Blast Waves

Measured: $z \Rightarrow d_L$, $\nu F_\nu$ flux, $t_\nu$ and jet angle $\theta_j$ for blob model

Total Energy Flux: $\Phi = \frac{dE}{dAdt} = \frac{L}{4\pi d_L^2}$

Spectral Energy Flux:

$$f_\nu (\text{erg } cm^{-2} s^{-1}) = \nu F_\nu$$

Blob: $\Phi \approx \delta_D^4 \frac{L'_\gamma}{4\pi d_L^2}$

$$f_\nu = \nu F_\nu = \frac{\delta_D^4 \epsilon' L'(\epsilon')}{4\pi d_L^2}, \quad r'_b = \frac{c \delta_D t_\nu}{1 + z}$$

Blast Wave: $\Phi \approx \Gamma^2 \frac{L'_\gamma}{4\pi d_L^2}$

$$f_\nu = \nu F_\nu = \frac{\Gamma^2 \epsilon' L'(\epsilon')}{4\pi d_L^2}, \quad R = \frac{c \Gamma^2 t_\nu}{1 + z}, \quad R' = R / \Gamma$$

Blob and blast wave framework are equivalent for opacity calculations.
Internal Radiation Fields

Instantaneous energy flux $\Phi$ (erg cm$^{-2}$ s$^{-1}$); variability time $t_v$, redshift $z$

Blob: \[
\Phi \approx \delta_D^4 \frac{L'_\gamma}{4\pi d_L^2}, \quad u'_\gamma \sim \frac{L'_\gamma t_{esc}'}{V'} \sim \frac{3d_L^2 \Phi}{\delta_D^4 r'_v c}, \quad t_{esc}' \sim r'/c \sim \Delta t' \approx \frac{\delta_D t_v}{1+z}
\]

\[
u'_\gamma \approx \frac{3d_L^2 (1+z)^2 \Phi}{\delta_D^6 t_v^2 c^3}
\]

\[n'_p(h)(\epsilon') \equiv \frac{3d_L^2 f_\epsilon}{m_e c^3 \epsilon' r'_v^2 \delta_D^4 r'_v^2}
\]

Blast Wave:

\[
u'_\gamma \equiv \frac{4\pi d_L^2 \Phi}{4\pi R^2 \Gamma^2 c} \equiv \frac{d_L^2 (1+z)^2 \Phi}{\Gamma^6 t_v^2 c^3}
\]

\[n'_\gamma(\epsilon') \equiv \frac{d_L^2 (1+z)^2 f_\epsilon}{m_e c^5 \epsilon' \Gamma^6 t_v^2}
\]

\[R' = R / \Gamma, R = \frac{c \Gamma^2 t_v}{1+z}, \quad \epsilon' \equiv \frac{(1+z)\epsilon}{\Gamma}
\]
Internal Magnetic Fields and Power

Internal energy density $u' = u'_{\gamma}/\varepsilon_e$ implies a jet magnetic field

$$B' \equiv \sqrt{8\pi \varepsilon_B u'_{\gamma} / \varepsilon_e}$$

$\varepsilon_e$ is fraction of total energy density in nonthermal electrons assumed to be producing the $\gamma$ rays

$\varepsilon_B$ is fraction of total energy density in magnetic field

Apparent Jet Power

$$P_j = 4\pi R^2 \beta c \Gamma^2 (u_B' + u_{par}' + u'_{\gamma})$$

Absolute Jet Power

$$P_j = 2\pi r_b'^2 \beta c \delta_D^2 \left( \frac{\Gamma^2}{\delta_D^2} \right) (u_B' + u_{par}' + u'_{\gamma})$$

$$r_b' \approx \frac{c\delta_D t_v}{1 + z}$$
3 month Fermi LAT data
>200 MeV

1 Year Fermi LAT data
10-100 GeV
Opacity : $\delta$-function approximation for Blob

$$\frac{d\tau_{\gamma\gamma}(\varepsilon'_1)}{dx'} \equiv \int_0^\infty d\varepsilon' \sigma_{\gamma\gamma}(s')n'_{ph}(\varepsilon'), \quad \sigma_{\gamma\gamma}(s') \equiv \frac{2}{3} \sigma_T \delta(s' - 2)$$

$$\tau_{\gamma\gamma}(\varepsilon'_1) = \frac{2}{3} \sigma_T r' \int_0^\infty d\varepsilon' \frac{\delta(\varepsilon' - 2 / \varepsilon'_1)}{\varepsilon'_1} n'_{ph}(\varepsilon') \quad \varepsilon' = 2 / \varepsilon'_1$$

$$\approx \frac{2}{3} \frac{\sigma_T r'n'_{ph}(2 / \varepsilon'_1)}{\varepsilon'_1}$$

$$n'_\gamma(\varepsilon') \equiv \frac{3d_L^2(1 + z)^2 f_\varepsilon}{m_e c^5 \varepsilon'^2 \delta_D^2 t_v^2}$$

$$n'_{ph}(\varepsilon') \equiv \frac{3d_L^2 f_\varepsilon}{m_e c^3 \varepsilon'^2 \delta_D^4 r'^2} \quad \Rightarrow \tau_{\gamma\gamma}(\varepsilon'_1) \equiv \frac{2\sigma_T}{3\varepsilon'_1} \frac{3d_L^2 f_\varepsilon}{m_e c^3 \varepsilon'^2 \delta_D^4 r'}$$

$$\varepsilon' = \frac{(1 + z)\varepsilon}{\delta_D}$$
Minimum Doppler factor approximation for Blob

\[ \tau_{\gamma\gamma} (\epsilon_1') \equiv \frac{2\sigma_T}{\epsilon_1'} \frac{d_L^2 f_\epsilon}{m_e c^3 \epsilon_1'^2 \delta_D^4 r'} \]

\[ \tau_{\gamma\gamma} (\epsilon_1') \equiv \frac{\sigma_T}{2} \frac{d_L^2 f_\epsilon \epsilon_1'}{m_e c^3 \delta_D^4 r'} \]

Minimum bulk Lorentz factor: \( \tau_{\gamma\gamma} (\epsilon_1) = 1 \)

\[ \Rightarrow \delta_{D,\text{min}} \equiv \left[ \frac{\sigma_T (1+z)^2 d_L^2 f_\epsilon \epsilon_1}{2m_e c^4 t_v} \right]^{1/6} \]

\[ \epsilon' \epsilon_1' \approx 2 \Rightarrow \hat{\epsilon} \equiv \frac{2\delta_D^2}{(1+z)^2 \epsilon_1} \]
\[ \delta_{D,\text{min}} \approx \left[ \frac{\sigma_T (1+z)^2 d_L^2 f_\delta \varepsilon_1}{2 m_e c^4 t_v} \right]^{1/6} \]

\[ \dot{\varepsilon} \equiv \frac{2\delta_D^2}{(1+z)^2 \varepsilon_1} \]

\[ z = 0.116, \quad d_L = 1.65 \times 10^{27} \text{ cm} \]

\[ t_v = 300 \, t_{5m} \text{ s} \]

Solve iteratively, quickly converges

\[ \delta_{D,\text{min}} \approx 32 \left[ \frac{(f_\delta / 10^{-10} \text{ erg s}^{-1} \text{ cm}^{-2}) E_1(\text{TeV})}{t_{5m}} \right]^{1/6} \]

\[ \tilde{E}(\text{keV}) \approx 0.6 \frac{(\delta_D / 36)^2}{E_1(\text{TeV})} \]

- Code of Finke et al. (2008)
- Includes internal $\gamma\gamma$ opacity but not pair reinjection
- Sensitive to EBL model
- Fit to 2006 flare
Synchrotron Self-Compton Model

Basic tool is one-zone synchrotron/SSC model with synchrotron self-absorption and internal pair production

Even this lacks pair reinjection; multiple self-Compton components

Deducing source redshift from high-energy spectra requires both good spectral model and good EBL model

What portion of synchrotron spectrum should be fitted?

Synchrotron/SSC model: Best fit model; parameter studies; extracting underlying electron distribution; variability analysis
Synchrotron/SSC Modeling

Approximations (in the one-zone model)

1. $\delta$-function approximation
   - zero-fold for synchrotron; 1 fold for SSC
   - Take KN effects into account by terminating integration when scattering enters the KN regime
   - Useful for analytic results; equipartition estimates; jet power calculations

2. Uniform approximation: $B$, $\delta_D$, and $R'$
   a. Integrate elementary synchrotron emissivity over electron $\gamma$-factor distribution (assumed uniform throughout sphere)
   b. Average synchrotron spectrum over blob to get target photon spectrum
   c. Compton-scatter synchrotron photons using (isotropic) Jones formula, valid throughout Thomson and KN regimes
   - Provides accurate absolute power estimates (photon, particle, B-field) given observing angle
   - for blazars, $\Gamma \approx \delta_D$; for radio galaxies inferred from observations
Synchrotron Self-Compton Modeling

Determine electron distribution from nonthermal synchrotron spectrum

Integrate electron spectrum over Crusius-Schlickeiser (1986) function to get accurate synchrotron emissivity;
See Finke et al. (2008)

Compton kernel in head-on approximation for SSC (Finke et al. 2008; Dermer et al. 2008)

Spatially-averaged emission

Synchrotron self-absorption for homogeneous sphere

\[
  f_{\varepsilon}^{\text{syn}} \approx f_{\varepsilon_s} \left[ \left( \frac{\varepsilon}{\varepsilon_0} \right)^{4/3} \left( \frac{\varepsilon_0}{\varepsilon_s} \right)^{a} H(\varepsilon; \varepsilon_0, \varepsilon_s) + \left( \frac{\varepsilon}{\varepsilon_s} \right)^{a} H(\varepsilon; \varepsilon_0, \varepsilon_s) + \left( \frac{\varepsilon}{\varepsilon_s} \right)^{b} H(\varepsilon; \varepsilon_s, \infty) \right]
\]
\(\gamma\gamma\) opacity and \(\Gamma_{\text{min}}\) for PKS 2155-304

<table>
<thead>
<tr>
<th>Model</th>
<th>(\delta_D)</th>
<th>(B) [mG]</th>
<th>(t_{\text{var}}) [s]</th>
<th>(L_j) ([10^{47}\text{ erg s}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>895</td>
<td>2.5</td>
<td>30</td>
<td>4.5</td>
</tr>
<tr>
<td>8</td>
<td>390</td>
<td>3.0</td>
<td>300</td>
<td>2.7</td>
</tr>
<tr>
<td>16</td>
<td>261</td>
<td>81</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>18</td>
<td>139</td>
<td>57</td>
<td>300</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Lower EBL

- Radio galaxy core emission well fit by sync./SSC model with \(\delta \approx \Gamma \approx \text{few}\)
- The \(\delta\)-unification problem
  - Decelerating Jet Model  
    (Georganopoulos & Kazanas 2003)
  - Spine and Sheath Model  
    (Ghisellini et al. 2005)
  - Colliding Shell Model

Standard one-zone synchrotron/SSC model

\((\gamma'_{\text{min}} = 100)\)

Doppler factor \(\delta \gg 100\) during flaring episodes
NGC 6251: FR1 MAGN

Perley et al. (1984)
First resolved extragalactic GeV source (after LMC)

10 times more energy in nonthermal protons/hadrons as electrons
FSRQ Modeling

At least three additional spectral components:
- Accretion disk
- EC Disk
- EC BLR

External radiation field provides a new source of opacity; need to perform Compton scattering and $\gamma\gamma$ opacity self-consistently

Opacity spectral break at a few GeV

Dermer et al. (2009)
The Peculiarly Constant GeV Spectral Break in 3C 454.3

- For MJD=55152-55261
- For MJD=55280-55300

- BPL, LogPar, Expcutoff

<table>
<thead>
<tr>
<th>$\Gamma_1$</th>
<th>$\Gamma_2$</th>
<th>$E_{\text{break}}$ (MeV)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\Gamma$</th>
<th>$E_{\text{b}}$ (MeV)</th>
<th>$P$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pm 0.01$</td>
<td>$3.05 \pm 0.06$</td>
<td>$1590^{+480}_{-180}$</td>
<td>$2.51 \pm 0.02$</td>
<td>$0.13 \pm 0.01$</td>
<td>$2.29 \pm 0.02$</td>
<td>$760 \pm 190$</td>
<td>$6000 \pm 600$</td>
</tr>
<tr>
<td>$\pm 0.02$</td>
<td>$3.23 \pm 0.14$</td>
<td>$2380^{+750}_{-270}$</td>
<td>$2.55 \pm 0.03$</td>
<td>$0.10 \pm 0.02$</td>
<td>$2.35 \pm 0.03$</td>
<td>$960 \pm 500$ MeV</td>
<td>$7700 \pm 1500$</td>
</tr>
</tbody>
</table>
Intrinsic spectral break in electron energy distribution with Compton-scattered accretion disk and broad line region radiation (Finke & Dermer 2010)

Robust solution, independent of dissipation radius, within BLR with wind-density profile (disk-wind)

$\gamma\gamma$ attenuation from H (13.6 eV) and He II (54.4 eV) recombination radiation deep within the BLR (Poutanen & Stern 2010)

Consistency of synchrotron and Compton-scattered radiation spectrum with external photon field?
Break due to Compton-Scattered Ly $\alpha$ Radiation?

$$E_{KN}(GeV) \approx 2.1 GeV / E_\star(10.2 eV)$$

Bonnoli et al. (2009)
GALEX and UVOT observations of strong Ly $\alpha$: $2 \times 10^{45}$ erg s$^{-1}$
Emission region size from reverberation mapping studies
⇒ Energy density of BLR

(cf. Georganopoulos et al. 2001)
PKS 2155-304

- X-ray selected BL Lac
- $z = 0.116$, $d_L = 540$ Mpc
- Detected by EGRET, AGILE
- August 2006: bright flares, detected by
  - Swift (Foschini et al. 2007) (3 ks/day)
  - HESS (Aharonian et al. 2007)
    - Variability timescale: ~5 minutes
- BeppoSAX observed variability ~ 1 hr (Zhang et al. 2002)
Temporal Variability

\[ R_s = \frac{2GM}{c^2} < \frac{ct_{\text{var}}}{(1 + z)} \]

Mini-jets
Magnetically-dominated jets

Colliding Shell Solution:

1. Variability
2. Unification
3. Light curves
4. UHECR acceleration

Can small-opening angle colliding shells avoid this problem?
3C 279

- Where are the $\gamma$-rays made?
- Monitor long-term behavior of light curve
- Correlates with changes in optical polarization and flux
- Highly ordered magnetic field over long timescale
- $\gamma$ ray dissipation location at multi-pc scale?

Abdo., et al. 2010, Nature, 463, 919

$3C\ 279$

$z = 0.538$
VHE $\gamma$ rays from Flat Spectrum Quasars

- 3C 279 ($z = 0.536$) with MAGIC
- PKS 1510-089 ($zz = 0.361$) with HESS
- PKS 1222+216 ($z = 0.432$) with Fermi, HESS, VERITAS

Variability of 70 – 400 GeV radiation on 10 min timescale

Two-zone scenario
(Tavecchio et al. 2011)

Strong nuclear pc-scale IR emission
($T = 1200$ K, $L_{IR} = 8\times10^{45}$ erg/s)

Malmrose et al. (2011)

Cosmic-ray induced emission on pc scale

Aleksic et al. (2011)
Exercise 1:  
Synchrotron/SSC model in the Thomson regime

Can measure 6 defining quantities for syn/SSC model:

\[ z, t_v \]

\[ \Gamma \approx \frac{1}{\epsilon_s} \sqrt{\frac{\epsilon_C}{c t_v B_{cr}} \sqrt{\frac{2 L_s}{c A_C}}} \]

\[ B \approx \frac{(1 + z) B_{cr} \epsilon_s^3}{\epsilon_C^{3/2}} \sqrt{c t_v B_{cr} \sqrt{\frac{c A_C}{2 L_s}}} \]

\[ \Gamma > \Gamma_{\text{min}} \]

\[ B_{cr} = \frac{m_e^2 c^3}{\epsilon \hbar} \approx 4.414 \times 10^{13} \text{ G} \]

Thomson regime

\[ \epsilon_C \epsilon_s \lesssim \left( \frac{\Gamma}{1 + z} \right)^2 \]

\( A_C = \frac{L_C}{L_s} \)
Exercise 2:
Nonthermal Electron Synchrotron/SSC model

If electrons are assumed to radiate the observed synchrotron $\nu F_\nu$ spectrum, then in the $\delta$-function approximation for synchrotron emissivity

$$f_{\epsilon}^{\text{syn}} = \frac{\delta_D^4 \epsilon' L' (\epsilon')}{4\pi d_L^2}, \quad \epsilon' L' (\epsilon') \approx \frac{4}{3} c \sigma_T \frac{B'^2}{8\pi} \gamma'^2 \times \gamma' N'_e (\gamma')$$

$$\epsilon' \approx \frac{B'}{B_{cr}} \gamma'^2, \quad \epsilon \approx \frac{\delta_D \epsilon'}{1 + z} \Rightarrow \gamma' \approx \sqrt{\frac{(1 + z) \epsilon B_{cr}}{\delta_D B'}}$$

Construct synchrotron/SSC model in $\delta$-function approximation
Relativistic jet physics

New results on blazars and radio galaxies:
1. LBAS / 1LAC/ 2LAC catalogs
2. Multi-GeV spectral softening in FSRQs, LBLs, IBLs; not XBLs
3. Multiwavelength quasi-simultaneous SEDs including GeV emission for radio galaxies, BL Lacs and FSRQs e.g.,
   1. FSRQs 3C 454.3, 3C 279
   2. BL Lacs: Mrk 421, PKS 2155-304
   3. Radio galaxies: Cen A, M87, 3C 84
4. 3C 279, PKS 1510-089: location of emission site; complexity of magnetic field
5. Use SED to constrain redshift from EBL model
6. Long (mo – yr) timescale light curves
7. High energy photons from blazar sources: minimum Doppler factor
8. Radio/\gamma-ray connection
Backup Slides
Jet Power

Jet power: total power available in jet (in observer frame)
- \( L_j = 2\pi r_b \beta \Gamma^2 c (u'_B + u'_p) \) (Celotti & Fabian 1993)
- \( dL_j / dB = 0 \rightarrow B_{\text{min}} \) (equipartition)
- \( B < B_{\text{min}} \rightarrow u'_p >> u'_B \) and \( f_{\text{SSC}} > f_{\text{syn}} \)

Synchrotron spectrum implies minimum jet power; additionally fitting \( \gamma \) rays gives deviation of model from minimum jet power
Monte Carlo Simulation of Synchrotron/SSC Model

Improved accuracy

Use accurate Compton kernel in the head-on approximation (Compton scattering, not inverse Compton scattering)

Mersenne Twister for Random Number Generator

Check uniformity assumption  
(cf. Gould 1979)

Can consider non-radial electron distributions

Realistic $\gamma\gamma$ opacity calculations

High energy tail for EBL studies

Photon conservation

$$\Xi_C \equiv y + y^{-1} - \frac{2\varepsilon_s}{\gamma\bar{\epsilon}y} + \left(\frac{\varepsilon_s}{\gamma\bar{\epsilon}y}\right)^2 \quad y \equiv 1 - \frac{\varepsilon_s}{\gamma}$$

$$\bar{\epsilon} = \gamma\epsilon(1 - \cos\psi)$$
Synchrotron with Photon Conservation

Standard parameters:

\[ n_e(\gamma) = k_{eo} \gamma^{-p} H(\gamma; \gamma_1, \gamma_2) \]

\[ R = 10^{15} \text{ cm}, \ p = 2.2 \]

\[ B = 1 \text{ G} \]

\[ k_{eo} = \frac{n_{eo}(p-1)}{\gamma_1^{1-p} - \gamma_2^{1-p}} \]

\[ n_{eo} = 10^{10} \text{ cm}^{-3} \]

\[ \gamma_1 = 10^5, \gamma_2 = 10^6 \]

Scattering in KN regime

Solves “line of death” problem in GRB physics?
Monte Carlo Synchrotron/SSC with Uniform Electrons and B-field

\[ \gamma_1 = 10^4, \gamma_2 = 10^5 \]

\[ \gamma_1 = 10^3, \gamma_2 = 10^4 \]

Comparison with \( \delta \)-function approximation

Discrepancies in amplitude

Discrepancies in high-energy cutoff (could improve it by using exponential cutoff in electron distribution)

Excellent agreement with numerical calculation (mean escape length = 3R/4)
Non-power law spectra

- First definitive evidence of a spectral break above 100 MeV
- General feature in FSRQs and many BLLac-LSPs
- Absent in BLLac-HSPs
- Broken power law model seems to be favored
- $\Delta \Gamma \sim 1.0 > 0.5 \rightarrow$ not from radiative cooling
- Favored explanation: feature in the underlying particle distribution
- Implications for EBL studies and blazar contribution to extragalactic diffuse emission


Challenge for modelers to account for the break and the relative constancy of spectral index with time
BL Lac and FSRQ: definition

- Classify an object as a BL Lac if the equivalent width (EW) of the strongest optical emission line is < 5 Å, e.g., [O II] \( \lambda 3727 \) and [O III] \( \lambda 5007 \). Classification of higher-redshift sources will preferentially use lines at shorter wavelengths (e.g., Ly\(\alpha\) \( \lambda 1216 \) and C IV \( \lambda 1549 \)) than for low-redshift sources (e.g., Mg II \( \lambda 2798 \) and H\(\alpha\) \( \lambda 6563 \)).

- A Ca II H/K break ratio \( C < 0.4 \),

- Wavelength coverage satisfies \( (\lambda_{\text{max}} - \lambda_{\text{min}})/\lambda_{\text{max}} > 1.7 \) so that at least one strong emission line would have been detected if it were present.

- Sources for which no optical spectrum or of insufficient quality to determine the optical classification are listed as “unknown type”
Radio Galaxies and Blazars

FR1/2: radio power/morphology correlation; dividing line at
\[ \approx 4 \times 10^{40} \text{ ergs s}^{-1} \]
\[ \approx (2 \times 10^{25}h^{-2}_{100} \text{ W/(Hz-sr) at 178 MHz}) \]

Mrk 501, \( z = 0.034 \)

BL Lacs vs. FSRQs:
- EW < 5 Å
- Ca H-K break < 0.4
- \((\lambda_{\text{max}} - \lambda_{\text{min}})/\lambda_{\text{max}} > 1.7\)

FR2 ↔ FSRQ

BL Lac vs. FSRQ
RQ vs. RL

Blazar Unification:
Padovani & Urry (1995)

FR1 ↔ BL Lac

W Comae

3C 296

3C 279, \( z = 0.538 \)
Write SSC as a function of: \( \delta_D, B, r_b', z, N_e(\gamma) \).

Use electron spectrum to calculate SSC using Jones (1968) formula

\( \nu F_\nu^{syn} \) gives \( N_e(\gamma) \)

(CS86 expression)

Internal and EBL absorption calculated

Leaves two unknowns to fit: \( \delta_D \) and \( B \)
Complex GeV Spectral Behavior

- Sampling separate FSRQ and BL Lac populations

Fig. 14.— SED of 3 bright blazars calculated in five energy bands, compared with the power law fitted over the whole energy range. Left: 3C454.3 (FSRQ), middle: AO 0235+164 (IBL), right: Mkn 501 (HBL)

Abdo et al. (2009) LBAS