Lecture 3. Radio Galaxies and Blazars, and the Extragalactic Background Light
Outline

“...curious straight ray...apparently connected with the nucleus by a thin line of matter.” H. E. Curtis, 1918

1. AGN, radio galaxies, blazars, and unification
2. Blazar Spectral Energy Distributions
3. Modeling blazar spectra
4. Extragalactic background light
5. Problems in blazar physics

M87 discovered and cataloged by Charles Messier on March 18, 1781 (234 yrs ago)

Distance; 16.4 Mpc
Black hole mass: $6.6(\pm 0.4) \times 10^9$ Solar masses
1. AGN, Radio Galaxies, Blazars, and Unification

AGN: active galactic nucleus

**Accretion Disk**
- Molecular Torus
- Shakura-Sunyaev Disk
- Magneto Rotational Instability
- Modified Accretion Disks
- Hot Pair Plasma ($T<10^9$ K)
- Fe Lines
- Broad Line Region/ Narrow Line Region

*Nonthermal particle acceleration not evident in radio-quiet AGNs*

**Jets**
- Formation and Collimation
- Relativistic Outflows
  - Compton catastrophe
  - Apparent superluminal motion
  - $\gamma\gamma$ opacity arguments
- Particle Acceleration Sites
  - Within BLR
  - Pc scale
  - Knots and hot spots
  - Lobes

Urry & Padovani (1995)
Blazars: Supermassive Black Holes with Relativistic Jets Pointed at Us

Causality argument for size of emission region

\[ R / c \leq \Delta t_{\text{var}} \quad R_s = \frac{2GM}{c^2} = 3 \times 10^9 (M / 10^9 M_{\odot}) \text{ cm} \]
\[ \Delta t_{\text{var}} \leq 1 \text{ day} \quad R_s / c \approx 10^4 (M / M_9) \text{ s} \]

\[ L_{\text{Edd}} = GMm_p c / \sigma_T \approx 10^{47} (M / M_9) \text{ erg} / \text{s} \]
\[ L_{\text{iso}} \approx 10^{48} (M / M_9) \text{ erg} / \text{s} \]

Abdo et al. 2010, Nature, 463, 920
Classes of AGN and Unification

Dermer & Giebels (2015)
Radio Galaxies and Blazars

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

![Graph of L vs. log(v(Hz))](image1)

**Mrk 501, z = 0.034**

![Image of Cygnus A](image2)
![Image of 3C 279](image3)

**3C 279, z = 0.538**

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

**W Comae**

Blazar Unification:
Padovani & Urry (1995)
2. Blazar Spectral Energy Distributions

**BL Lacs:** emission to VHE/TeV energies

BL Lacergz = 0.033

**FSRQs:** cutoffs at GeV with VHE episodes

FSRQerg/s

Two-humped SED
Classifying Fermi AGNs

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

Essentially all FSRQs are LSPs

Searching for the Hertzsprung-Russell Diagram in blazar studies

Inverse correlation between $E_{\text{peak}}$ and luminosity (Fossati et al. 1998)
- LSP blazars powerful
- HSP blazars weak

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)
Blazar Sequence

- Searching for the Hertzsprung-Russell Diagram in blazar studies
- Inverse correlation between $E_{\text{peak}}$ and luminosity (Fossati et al. 1998)
  - LSP blazars powerful
  - HSP blazars weak
- 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)
- Searching for the Hertzsprung-Russell Diagram in blazar studies
- Inverse correlation between $E_{\text{peak}}$ and luminosity (Fossati et al. 1998)
  - LSP blazars powerful
  - HSP blazars weak
- 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)
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
\( \gamma \)-Ray Galaxy Luminosity and the Fermi Blazar Divide

Fermi blazar divide
(Ghisellini et al. 2009)

Misaligned AGNs
(host galaxies of blazars)

Star forming galaxies
3. Blazar Modeling

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

**Leptonic jet models:**
- Nonthermal synchrotron radiation for radio through optical (low-energy hump)
- Compton scattering by jet electrons to make high-energy $\gamma$-ray component (high-energy hump)

**Lepto-Hadronic jet models:**
- Nonthermal synchrotron radiation for radio through optical (low-energy hump)
- Secondary nuclear production
  $$ p+N \rightarrow \pi^o, \pi^\pm \rightarrow \gamma, \nu, n, e^\pm $$
- Proton and ion synchrotron radiation
  $$ p+B \rightarrow \gamma $$
- Photomeson production
  $$ p\gamma \rightarrow \pi^o,\pi^\pm \rightarrow \gamma, \nu, n, e^\pm $$

Neutrons escape to become UHECRs
Nonthermal synchrotron paradigm

Associated SSC $\gamma$-ray component (BL Lac objects) and SSC/EC components (FSRQs)

**Target photon sources:**
- Accretion-disk radiation
- Broad-line region radiation
- IR radiation from molecular torus

**Energy Sources:**
1. Accretion Power
2. Rotation Power

Relativistic plasma outflows: $\Gamma \gg 1$
Apparent Luminosities and Energies

Apparent vs. Absolute luminosities:
\[ L_{\text{abs}} \approx L_{*,\text{iso}} \times \text{beaming factor } f_b \]
Top hat 2-sided jet:
\[ f_b = (1-\cos \theta_j) \]

\[ \theta_j = 0.1 \text{ (5.7°), } f_b \approx 1/200 \]
\[ \theta_j = 0.01 \text{ (0.57°), } f_b^{-1} \approx 1/20,000 \]

Measure apparent luminosity (assumed to be directed into 4\(\pi\) sr):

\[ L_{*,\text{iso}} = 4\pi d_L^2 \Phi \]
\[ L_{*,\text{abs}} = 4\pi d_L^2 \Phi f_b \]
Compactness

- Puzzle: how to get $\gamma$ rays out of compact region?

$\gamma \gamma$ opacity  
$\gamma + \gamma_1 \rightarrow e^+ + e^-$

Threshold:  
$\varepsilon_1 \equiv \left( \frac{h \nu}{m_e c^2} \right) \left( \frac{h \nu_1}{m_e c^2} \right) > 2$

$$n_\gamma \approx \frac{L_\gamma}{4\pi R^2 cE_\gamma}$$

$\tau_{\gamma'} \approx \sigma_{\gamma'} n_\gamma R, \quad \sigma_{\gamma'} \approx \sigma_T$

Compactness parameter:  
$$\ell \approx \frac{L_\gamma \sigma_T}{4\pi R m_e c^3 \varepsilon}$$

$$\ell \approx \tau_{\gamma'} \approx \frac{\sigma_T L_\gamma}{4\pi m_e c^4 \Delta t_{\text{var}}} \approx 10^3 \frac{L_\gamma}{(10^{48} \text{ erg} / \text{s})} \frac{\Delta t_{\text{var}} (d)}{}$$

superluminal motion in 3C 120
Solution: Bulk Relativistic Motion

Causality relation for stationary sources:

\[ R < c \Delta t_{\text{var}} \]

- Suppose relativistic spherical shell briefly illuminated, e.g., by shell collisions
- Due to strong beaming, only see emission emitted within Doppler cone \( \theta_{\text{Doppler}} \approx 1/\Gamma \)

\[ c \Delta t_{\text{var}} \approx R(1 - \cos \theta_{\text{Doppler}}) \approx R \theta_{\text{Doppler}}^2 / 2 \approx R / 2 \Gamma^2 \]

\[ \Rightarrow R < 2 \Gamma^2 c \Delta t_{\text{var}} \]

Emission size \( \sim \Gamma^2 \) larger than values inferred for stationary region
Doppler Factor

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

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

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

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

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

\[ \theta = 0 \Rightarrow \Delta t = \frac{\Delta x}{\beta c} (1 - \beta) \rightarrow \frac{\Delta x}{\Gamma^2 c} \]

\[ dt = \frac{dt'}{\delta_D} \]

\[ \epsilon = \delta_D \epsilon' \Rightarrow \]

\[ \frac{d \epsilon}{d \epsilon'} = \delta_D = \frac{dt'}{dt} \]
Variability and Source Size

Source size from direct observations:

\[ r'_b \simeq d_A \theta \simeq 2 \left( \frac{d_A}{10^{27} cm} \right) \theta (mas) \, pc \]

Source size from temporal variability:

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

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

Variability timescale implies maximum emission region size scale
Relativistic Bulk Motion in Blazars

What is $\Gamma$, and why is it important?

After redshift $z$, $\Gamma$ is the most important property to make the extreme behavior of blazars comprehensible.

Doppler factor $\delta_D = [\Gamma(1 - \beta \cos \theta)]^{-1}$

$$L \approx \delta_D^4 L' \approx 4\pi c R'^2 \delta_D^4 u'; \quad \varepsilon \approx \Gamma \varepsilon'$$

$$R' \approx \delta_D c t_{\text{var}} \Rightarrow L \sim c^3 \delta_D^6 t_{\text{var}}^2 u'$$

$$u'_\gamma \propto \frac{L'_\gamma}{R'^2} \propto \frac{L_\gamma}{\delta_D^6}$$

To be optically thin to $\gamma\gamma$ absorption, $\Gamma > 10$ in Blazars
Particle Acceleration and Radiation in Leptonic Blazar Models

\[ \frac{\partial n(\gamma; t)}{\partial t} + \frac{\partial}{\partial \gamma} \left[ \dot{\gamma} n(\gamma; t) \right] + \frac{n(\gamma; t)}{t_{\text{esc}}(\gamma, t)} = \dot{n}(\gamma; t) \]

The synchrotron flux is then given by

\[ f_{\epsilon}^{\text{syn}} = \frac{\delta_D^4 \epsilon_4 J_{\text{syn}}(\epsilon')}{4 \pi d_L^2} = \frac{\sqrt{3} \delta_D^4 \epsilon_4 \epsilon_3 B}{4 \pi h d_L^2} \int_1^\infty d\gamma' N_{\epsilon}^{'}(\gamma') R(\chi). \]

\[ f_{\epsilon}^{\text{SSC}} = \left( \frac{3}{2} \right)^3 \frac{d_L^2 \epsilon_{12}^2}{R_b^2 c \delta_D^4 U_B} \int_0^\infty d\epsilon' f_{\epsilon}^{\text{syn}} \]

\[ \times \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma' \frac{F_C(q, \Gamma_e) f_{\epsilon}^{\text{syn}}}{\gamma'^5}, \]

\[ f_{\epsilon} = \frac{3}{4} \frac{c \sigma_T \epsilon_{12}^2}{d_L^2} \delta_D^3 \int_0^\infty d\epsilon_s \frac{u_s(\epsilon_s)}{\epsilon_s^2} \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma' \frac{N_{\epsilon}^{'}(\gamma', \Omega')}{\gamma^2} F_C(q, \Gamma_e) \]

1. Inject power laws and cool
2. Separate acceleration and radiation zones
3. Single zone; exclude radio
4. Power law injection
5. Nonlinear losses
6. Adiabatic expansion
7. Light travel time effects
8. Cascading/\gamma\gamma pair production
9. Multizone/spine-sheath
10. Anisotropic effects
11. Reverberation/echo

Boettcher & Chiang (2002)
Finke et al. (2008)
Dermer & Menon (2009)
Spectrum and Jet Physics

- **BL Lacs**: synchrotron/SSC model fits
  - Abdo et al. 2011a

- **FSRQs**: synchrotron/SSC + EC
  - Bonnoli et al. 2009
  - Böttcher et al. 2009
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

SSC fit to combined Fermi-MAGIC campaign on Mrk 421

Two one-zone model fits are shown, with different variability times of 1 hour and one day
Cen A Core and Lobes

- 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
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)
1 Year Fermi LAT data
10-100 GeV
4. The Extragalactic Background Light (EBL)

Infrared/optical EBL from past stellar activity and dust absorption and re-radiation (attenuates TeV radiation)

Difficult to directly measure

Provides a source of $\gamma\gamma$ opacity in intergalactic space through the process

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

Gould & Schréder 1966; Stecker, de Jager, Salamor
Blazars and the EBL

Ajello/Fermi Collaboration 2012
EBL Modeling


2. **Semi-analytic merger-tree models of galaxy formation**

3. **Star formation and dust re-radiation**

Stellar emissivity at redshift $z$:

$$\varepsilon j^\text{stars} (\varepsilon; z) = \varepsilon^2 f_{\text{esc}} (\varepsilon) \int dm \xi(m) \left. \frac{dt^*}{dz_1} \right|_{z}^{z_{\text{max}}} \psi(z_1) N^*_\text{e} (\varepsilon; m, t^*(z, z_1))$$

**Photon Escape Fraction** (using $\sim 10^5$ galaxies in Millennium Galaxy Catalog; Driver 2008)

**Initial Mass Function**

$\propto m^{-2.2}$ at $m > 0.5$, $\sim$Salpeter; $\propto m^{-0.5}$ at $0.1 < m < 0.5$: Baldry & Glazebrook 2003)

**Star Formation Rate** per comoving volume

(Hopkins & Beacom 2006 using Cole et al. 2001 parametrization)

**Stellar photon production rate** using stellar radii and luminosities, and time on various parts of HR diagram

(Eggleton et al. 1989 + corrections)
EBL from Stars and Dust

\[
e^{\ast}_{\text{j}}(\varepsilon; z) = \varepsilon^2 f_{\text{esc}}(\varepsilon) \int dm \xi(m) \int_{0}^{z_{\text{max}}} \frac{dt_*}{dz_1} \psi(z_1) \dot{N}_*(\varepsilon; m, t_* (z, z_1))
\]

\[
e^{\text{dust}}_{\text{j}}(\varepsilon; z) = \frac{15}{\pi^4} \sum_{n=1}^{3} \frac{f_n \varepsilon^4}{\Theta_n^4 [\exp(\varepsilon / \Theta_n) - 1]} \int_{0}^{\infty} d\varepsilon' \left[ \frac{1 - f_{\text{esc}}(\varepsilon')}{f_{\text{esc}}(\varepsilon')} \right] j^{\text{stars}}_{\varepsilon}(\varepsilon'; z)
\]

**Dust Parameters**

<table>
<thead>
<tr>
<th>Component</th>
<th>( n )</th>
<th>( f_n )</th>
<th>( T_n ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm large grains</td>
<td>1</td>
<td>0.60</td>
<td>40</td>
</tr>
<tr>
<td>Hot small grains</td>
<td>2</td>
<td>0.05</td>
<td>70</td>
</tr>
<tr>
<td>PAHs</td>
<td>3</td>
<td>0.35</td>
<td>450</td>
</tr>
</tbody>
</table>

Comparison with stellar population synthesis model (Bruzal & Charlot 2003) for stars all born at the same time with Salpeter IMF.
\textbf{\(\gamma\)-ray Constraints on EBL Models}

1. Deabsorbed VHE (\(> 100\ \text{GeV}\)) spectrum softer than, e.g., \(-1.5\)

2. Deabsorbed VHE spectrum bounded by Fermi spectrum extrapolated into VHE range

3. Use Fermi measurements to constrain UV EBL; look for Ly edge in the IGRB (cf. Oh 2001)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{gamma-ray_constraints.png}
\caption{\(\gamma\)-ray Constraints on EBL Models}
\end{figure}

\textit{Finke, Razzaque, Dermer 2010}
Highest Energy Photons

- Highest energy photons compared to $E_{\gamma}(z;\tau_{\gamma\gamma} = 1)$ curves
- $E_{\gamma}(z;\tau_{\gamma\gamma} = 1) \sim 100 \text{ GeV}/z$ (red line)

- Update with recent Fermi/IACT data
Deabsorbed Blazar Spectra

- Deabsorbed spectrum shows spectral hardening: evidence for new spectral component?
- Hard spectrum arises for a wide range of EBL models
- Values consistent with $\Gamma_{\text{int}} > -1.5$ (except for Stecker’s models)
5. Problems in Blazar Physics

1) Short variability times of luminous BL Lac objects
2) Unusual weakly variable BL Lac class
3) Distinct spectral components revealed by deabsorption of blazar VHE spectra
4) Flattening at moderate redshift in the Stecker-Scully relation showing the GeV - TeV spectral index difference versus redshift
5) Conflicting results for the location of the γ-ray emission site in blazars
6) VHE (> 100 GeV) emission from distant FSRQs γ rays formed by $\gamma\gamma \rightarrow e^+e^-$ with photons of ambient radiation fields
Strongly Variable Class of BL Lac Objects

- **Strongly variable class**
  - Mrk 421, $z = 0.03$
  - Mrk 501, $z= 0.033$
  - PKS 2155-305, $z = 0.116$
  - $t_{\text{var}} < R_S/c$, $L > L_{\text{EDD}}$
  - Extreme sources

- $R_S/c = 10^4 M_9$ s
- $t_{\text{var}} \sim 5$ min = 300 s
- $\Rightarrow (?) M << 10^8 M_0$
Weakly Variable Class of TeV BL Lac Objects

Weak Fermi LAT fluxes

1ES 0229+200 \( z = 0.14 \)
1ES 0347-121 \( z = 0.186 \)
1ES 1101-232 \( z = 0.14 \)
1ES 0548-322 \( z = 0.069 \)
RGB J0152+0.17 \( z = 0.08 \)

Compton-scattered CMBR from extended jet/lobe produces weakly variable TeV \( \gamma \) rays

Böttcher, CD, Finke 2008
High-Redshift VHE Blazars and the Stecker-Scully Relation

- GeV-TeV Spectral index difference $\Delta \Gamma$
  (cf. Sanchez et al. 2013)
Gamma-ray and Cosmic-ray Induced TeV emissions from Jetted Sources

Mechanism for making

Weakly variable cascade radiation

Hard VHE component

UHECR protons with energies $\sim 10^{19}$ eV make $\sim 10^{16}$ eV $e^\pm$ that cascade in transit and Compton-scatter CMBR to TeV energies

Essey, Kalashev, Kusenko, Beacom (2010, 2011)
Maximum UHECR energies in blazars and GRBs

Standard one-zone synchrotron/SSC model for BL Lac objects and GRBs

Parameters: $B'$, $\delta$, $R' \approx c \delta t_{\text{var}}$

Hillas condition: $E_A^{\text{max}} \approx Z e B' \Gamma R'$

GRBs can accelerate UHECR protons to $> 10^{20}$ eV

Transition predicted from proton composition to heavy ion composition at $\sim 10^{19}$ eV in BL Lac objects…

Provided ions can escape the acceleration zone

---

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>Epoch</th>
<th>$E_A^{\text{max}}(t)/Z[10^{19}]$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CenA(core)</td>
<td>0.00183</td>
<td>2009</td>
<td>0.01-4</td>
</tr>
<tr>
<td>M87</td>
<td>0.00436</td>
<td>2009</td>
<td>0.05</td>
</tr>
<tr>
<td>NGC1275</td>
<td>0.0179</td>
<td>Oct. 2010$^d$</td>
<td>5</td>
</tr>
<tr>
<td>NGC6251</td>
<td>0.024</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>Mrk421</td>
<td>0.03</td>
<td>19 March 2001</td>
<td>0.3</td>
</tr>
<tr>
<td>Mrk501 (I$^e$, 1997)</td>
<td>0.0337</td>
<td>16 April 1997</td>
<td>0.1-2</td>
</tr>
<tr>
<td>Mrk501 (I$^e$, 1997)</td>
<td>0.0337</td>
<td>7 April 1997</td>
<td>2</td>
</tr>
<tr>
<td>Mrk501 (I$^e$, 2007)</td>
<td>0.0337</td>
<td>2007</td>
<td>0.2</td>
</tr>
<tr>
<td>Mrk501 (I$^e$, 2009)</td>
<td>0.0337</td>
<td>2009</td>
<td>0.2-0.7</td>
</tr>
<tr>
<td>1ES1959+650(h$^e$)</td>
<td>0.047</td>
<td>Sept 2001-May 2002</td>
<td>0.1-3</td>
</tr>
<tr>
<td>1ES1959+650(l$^e$)</td>
<td>0.047</td>
<td>23-25 May 2006</td>
<td>1-2</td>
</tr>
<tr>
<td>PKS2200+420/BL Lac</td>
<td>0.069</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>PKS2005-489</td>
<td>0.071</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>WComae</td>
<td>0.102</td>
<td>7-8 June 2008</td>
<td>0.4-0.7</td>
</tr>
<tr>
<td>PKS2155-304</td>
<td>0.116</td>
<td>28-30 July 2006</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Murase, CD, Takami, Migliori (2012)
Electromagnetic Signatures of UHECRs

Photon-induced cascade in IGM

UHECR-induced cascade in IGM

FIG. 1.— Spectra of VHE $\gamma$-ray-induced cascade emission for various source redshifts. We assume the total $\gamma$-ray luminosity of $L_{\gamma} = 10^{45}$ erg s$^{-1}$ with $\beta = 2/3$ and $E_{\text{max}} = 100$ TeV. The low-IR EBL model of Kneiske et al. (2004) is used here.

Polisensky & Ricotti 2011

Murase et al. 2012
>10 GeV Sources Explained by Cascade Emission

- **GeV-TeV sources**
  - EBL effects greater on more distant blazars

- **Model >10 GeV Fermi-LAT emission by cascades**
  - \( \gamma\gamma \) / Compton cascade
    - Kneiske et al. (2004) EBL models
    - Assume no suppression from IGMF \( (B_{\text{IGMF}} < 10^{-15} \text{ G}) \)
    - Intrinsic spectrum \( F(E_{\gamma}) \propto E_{\gamma}^{-1.76} \), \( 5.6 \text{ GeV} < E_{\gamma} < 100 \text{ TeV} \)

- **UHECR-induced cascade**
  - Bethe-Heitler pair production
  - Assume no suppression from IGMF \( (B_{\text{IGMF}} < 10^{-12} \text{ G}) \)
  - UHECR proton spectrum:
    \[ F(E_p) \propto E_p^{-2.6}\exp(-E_p/10^{19} \text{ eV}) \]

\[ \text{KUV 00311-1938 (} z = 0.61 \)\]

- Normalization imposed to fit > 10 GeV Fermi-LAT spectrum from cascade emission
- Definitive test of UHECR Hypothesis with CTA
1. Radio-\(\gamma\) correlations
2. Optical polarization angle swings: 3C 279, PKS 1510-089, OJ 287
3. Rapid variability, large luminosity implies inner jet origin of \(\gamma\) rays

\[
R < c \Gamma^2 \Delta t_{\text{var}} \approx 0.05(\Gamma / 100)^2 (\Delta t_{\text{var}} / 10 \text{ min}) \; \text{pc}
\]

\[
R > R_{\gamma\gamma} \Rightarrow R >> R_{BLR} \approx 0.1 \; \text{pc}
\]

4C +21.35
The Blazar Paradigm: Summary

- **Standard blazar paradigm:** AGNs with jets explained by leptonic Compton-synchrotron processes in relativistic collimated plasma; hadronic effects not established either by modeling or from (e.g., neutrino) observations

- **Problems with the blazar paradigm**
  - Deabsorbed spectra of distant \( z > 0.1 \) TeV blazars show unexplained hard emission component
  - \( \Delta \Gamma = \Gamma_{\text{GeV}} - \Gamma_{\text{TeV}} \) relation violated
  - Location of \( \gamma \)-ray emitting regions in blazars
  - Rapid variability in BL Lac objects
  - Existence of a weakly variable BL Lac class
  - VHE emission from FSRQs
  - Synchrotron puzzle

- **Directions forward**
  - New thinking about particle acceleration
  - UHECRs in blazar can potentially solve some of these problems
  - New physics
Backup Slides
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:

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

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

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

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

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

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

**Blob:**

$$\Phi \approx \delta_d^4 \frac{L'_\gamma}{4\pi d_L^2}, \quad u'_\gamma \sim \frac{L'_\gamma t'_{esc}}{V'}, \quad t'_{esc} \sim \frac{3d_L^2 \Phi}{\delta_D r'^2 c}, \quad \Delta t' \approx \frac{\delta_D t_v}{1+z}$$

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

$$n'_\gamma (\varepsilon') \equiv \frac{3d_L^2 f_\varepsilon}{m_e c^3 \varepsilon'^2 \delta_D r'^2}$$

**Blast Wave:**

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

$$n'_\gamma (\varepsilon') \approx \frac{d_L^2 (1+z)^2 f_\varepsilon}{m_e c^5 \varepsilon'^2 \Gamma^6 t_v^2}$$

$$R' = R / \Gamma, \quad R = \frac{c \Gamma^2 t_v}{1+z}, \quad \varepsilon' \approx \frac{(1+z)\varepsilon}{\Gamma}$$
Internal Magnetic Fields and Power

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

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

$\varepsilon_e$ 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

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

$$r_b' \approx \frac{c \delta_D t_v}{1 + z}$$
\[ \tau_{\gamma\gamma}(\varepsilon_1') \approx \frac{2}{3} \sigma_T r' \int_0^\infty d\varepsilon' \frac{\delta(\varepsilon' - 2 / \varepsilon_1')}{\varepsilon_1'} n'_{ph}(\varepsilon') \quad \varepsilon' = 2 / \varepsilon_1' \]

\[ \tau_{\gamma\gamma}(\varepsilon_1') \approx \frac{2}{3} \sigma_T r' n'_{ph}(2 / \varepsilon_1') \]

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

\[ n'_{ph}(\varepsilon') \approx \frac{3d_L^2f_\varepsilon}{m_e c^3 \varepsilon'^2 \delta_D r'^2} \quad \Rightarrow \tau_{\gamma\gamma}(\varepsilon_1') \approx \frac{2\sigma_T}{3\varepsilon_1'} \frac{3d_L^2f_\varepsilon}{m_e c^3 \varepsilon_1'^2 \delta_D r'} \]

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

\[ \tau_{\gamma'}(\varepsilon'_1) \approx \frac{2\sigma_T}{\varepsilon'_1} \frac{d_L f_{\varepsilon}}{m_e c^3 \varepsilon'^2 \delta_D r'} \]

\[ \tau_{\gamma'}(\varepsilon'_1) \approx \frac{\sigma_T}{2} \frac{d^2_L f_{\hat{\varepsilon}} \varepsilon'_1}{m_e c^3 \delta^4_D r'} \]

\[ \tau_{\gamma'}(\varepsilon_1) \approx \frac{\sigma_T (1+z)^2 d^2_L f_{\hat{\varepsilon}} \varepsilon_1}{2 m_e c^4 \delta^6_D t_v} \]

Minimum bulk Lorentz factor: \( \tau_{\gamma'}(\varepsilon_1) = 1 \)

\[ \Rightarrow \delta_{D,\text{min}} \approx \left[ \frac{\sigma_T (1+z)^2 d^2_L f_{\hat{\varepsilon}} \varepsilon_1}{2 m_e c^4 t_v} \right]^{1/6} \]

\[ \varepsilon' \varepsilon'_1 \approx 2 \Rightarrow \hat{\varepsilon} \approx \frac{2 \delta^2_D}{(1+z)^2 \varepsilon_1} \]
\[ \delta_{D, \text{min}} \approx \sqrt[1/6]{\frac{\sigma_T (1+z)^2 f_\delta \varepsilon_1}{2m_e c^4 t_v}} \]

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

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

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

Solve iteratively, quickly converges

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

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

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