Extragalactic Diffuse Emissions

Chuck Dermer

GLAST IDS
Naval Research Laboratory

GLAST Symposium
Stanford U., West Palo Alto
February 8, 2007

1. GLAST Analysis of High Latitude Sources
2. EGRET blazar model statistics $\Rightarrow$ predictions for GLAST
3. Sources of unresolved/diffuse extragalactic $\gamma$-ray intensity
4. Hadronic Signatures in Blazars and GRBs
5. Correlation of Fluxes: joint $\gamma\gamma$ and photohadronic $\nu$ constraints
6. Black hole demography, cosmic ray origin
EGRET Legacy

3EG catalog: 270 sources, 66 high confidence blazars  Hartman et al. (1999)  (Cen A)

(~ 130 blazars: Romani)

Third EGRET Catalog

E > 100 MeV

Ground γ Telescopes

> 15 TeV/XBL blazars
1 radio galaxy: M87

Galactic Plane Scan
New LAT Performance Parameters: $A_{\text{eff}}$

![Graph showing on-axis effective area vs. true energy for EGRET and GLAST LAT telescopes.](image-url)
Angular Resolution vs. True Energy at Normal Incidence

New LAT Perform. Parameters: PSF

Paredes et al. (2000)
GLAST data analysis

EGRET analysis: >100 MeV
(background-limited for weak sources)

\[ \phi_{-8} = \phi / 10^{-8} \, \text{ph} (>100 \, \text{MeV}) \, \text{cm}^{-2} \, \text{s}^{-1} \]

\( \sim 7 \times 10^{-12} \, \phi_{-8} \, \text{ergs cm}^{-2} \, \text{s}^{-1} \) for a flat \( \nu F_{\nu} \) spectrum with \( \alpha_{ph} = 2 \)

EGRET: \( \phi_{-8} \approx 15 \); 2-week pointing—\( 1/24^{th} \) of the full sky

(\( \nu F_{\nu}^{\text{thr}} \sim 10^{-10} \) ergs cm\(^{-2} \) s\(^{-1} \))

GLAST: \( \phi_{-8} \approx 15 \) in \( \sim 1 \) day over full sky (\( \nu F_{\nu}^{\text{thr}} \sim 10^{-10} \) ergs cm\(^{-2} \) s\(^{-1} \))

Sub-hour scale variability when \( \phi_{-8} > 200 \)

\# of \( \phi_{-8} > 200 \) blazar flares: few per week (Dermer & Dingus 2004)

Bias toward hard spectrum GeV sources at low fluxes: XBLs over FSRQs?
Blazar Statistics

Redshift Distribution of EGRET $\gamma$-Ray Blazars

Uniform exposure:
EGRET all-sky survey
Fichtel et al. (1994):
1EG catalog

EGRET blazar sample:
46 FSRQs
14 BL Lac Objects

thanks to Stan Davis
thanks to Stan Davis
Two-week on-axis sensitivity of EGRET:

\[ \approx 15 \times 10^{-8} \text{ ph}(>100 \text{ MeV}) \text{ cm}^{-2} \text{ s}^{-1} \]

\[ \approx 10^{-10} \text{ erg cm}^{-2} \text{ s}^{-1} \]

(100 MeV – 5 GeV)
**Blazars: the Platonic Ideal**

**Basic Radiation Physics:**

\[ \nu F_\nu = f_\epsilon \left( \text{ergs cm}^{-2} \text{ s}^{-1} \right) \]

**Threshold condition:**

\[ f_\epsilon^{\text{proc}} = \frac{\ell'_e \delta_D \epsilon_\nu}{d_L^2(\zeta)} \geq f_\epsilon \]

Telescope sensitivity

\[ \epsilon_z = \left( \frac{h \nu}{m_e c^2} \right) (1 + z) \]

\[ \delta_D = \left[ \Gamma (1 - \beta \mu) \right]^{-1}, \alpha_\nu = \left( 3 - p \right) / 2 \]

Comoving directional luminosity

\[ \ell'_e \left( \text{ergs s}^{-1} \text{ sr}^{-1} \right) \]

1. synchrotron/SSC
2. external Compton

\[ q = \begin{cases} 
\frac{(p + 5)}{2}, & \text{synchrotron/SSC} \\
 p + 3, & \text{EC} 
\end{cases} \]
Model redshift and size distributions of EGRET blazars

\[
\frac{d\dot{N}_{bl}}{d\Omega}(> f_{\epsilon}) = 2c\dot{n}_{bl} \int_{0}^{\infty} \frac{dt_{*}}{d\zeta} \left| \frac{d^{2}L(z)}{dz^{2}}\frac{\Sigma_{bl}(z)}{(1+z)^{2}} \right| \\
\times \int_{1}^{\infty} d\Gamma N(\Gamma; z) \int_{0}^{\infty} \ell_{e}' N(\ell_{e}' ; z) [1 - \max(-1, \mu)]
\]

Simplest model: fixed $\Gamma$, fixed $\ell_{e}'$ (no luminosity evolution)

Blazar Formation Rate analytic
Blazar Cosmology

1. Comoving Density (or Rate Density) Evolution
2. Luminosity Evolution

Blazar Formation History (BFH)

Constant Comoving Rate

Star Formation Rate (SFR)

IR,8 (Sanders 2004)

SFH BL
Fit of FSRQ Model to Redshift Distribution

 mono- parameter
 L_\star Blazar
 SFR IR,4

FSRQ
\Gamma = 10, p = 3.4
\Gamma_e = 2.5 \times 10^{39} \text{ ergs s}^{-1} \text{ sr}^{-1}
EC, BFR IR,4
\phi_{-8} = 25
Size Distribution of Model FSRQ

FSRQ
Γ = 10, p = 3.4
I' e = 2.5 × 10^{39} ergs s^{-1} sr^{-1}
EC, BFR IR,4
φ_{-8} = 25

N(>φ_{-8})

N_{tot}

Peak flux φ_{-8} [10^{-8} (ph > 100 MeV) cm^{-2} s^{-1}]
Redshift and Size Distributions of BL Lac Objects

Require negative density evolution (fewer BL Lacs at early times)

Positive luminosity evolution (brighter at early time)
Blazar Main Sequence

Evolution from FSRQ to BL Lac Objects in terms of a reduction of fuel from surrounding gas and dust

Sambruna et al. (1996); Fossati et al. (1998)
Ghisellini et al. (1998)
Böttcher and Dermer (2000)
Cavaliere and d’Elia (2000)

BL Lac objects are late stages of FSRQs: in accord with analysis of EGRET data
(1) Blazar main sequence valid? (2) BL Lac BH Masses > FSRQ BH masses?
Model Redshift Distribution of EGRET γ-Ray Blazars

Number of blazars vs Redshift z

BLs
FSRQs
Redshift Predictions for GLAST $\gamma$-Ray Blazars

GLAST predictions at 1 GeV
1, 3, 10, 30, 100 x EGRET
GLAST reaches sensitivity of $0.4 \times 10^{-8}$ ph($>100$ MeV)/cm$^2$ s in one year

~700 FSRQ/FR2s and ~150 BL/FR1s by end of first year of operation

see Dermer (2006), ApJ, in press (see astro-ph) for details
Peak flux size distribution of EGRET blazars for two-week pointings during the all-sky survey

Dotted curves: Mücke and Pohl (2000)

Stecker (priv. comm., this conference) predicts 8000-10000 GLAST blazars based on Stecker & Salamon (1996) treatment
**Blazar Contribution to Unresolved/Diffuse γ-Ray Background**

**Data:** Sreekumar et al. (1998)
Strong, Moskalenko, & Reimer (2000)

- **EGRET Analysis** (Sreekumar et al. 1998)
  (Atwood GLAST symposium talk 2007)
- **GALPROP Model** (Strong, Moskalenko, & Reimer 2000)
  Analysis herein:
  BL Lacs: ~2 - 4% (at 1 GeV)
  FSRQs: ~ 10 - 15%

![Graph showing the contribution of blazar to the background γ-rays.](image)
GRB Contribution to the Diffuse Extragalactic $\gamma$-Ray Background

Truong Le poster

• Ratio of EGRET spark chamber fluence to $>20$ keV BATSE fluence: (Dingus 1995, Catelli & Dingus 1997)

1. GRB 910503: $\rho = 1.7\%$
2. GRB 910601: $\rho = 2.8\%$
3. GRB 930131: $\rho = 15\%$
4. GRB 940217: $\rho = 0.8$-2\%
5. GRB 940301: $\rho = 3.4\%$

Average: $<\rho> \approx 5\%$

until $\rho \approx 10$, cf. Casanova Dingus & Zhang (2006)
Unresolved $\gamma$-Ray Background

BL Lacs: $\sim$2 - 4% (at 1 GeV)
FSRQs: $\sim$ 10 - 15%

Star-forming galaxies (Pavlidou & Fields 2002)
Starburst galaxies (Thompson et al. 2006)
Pulsar contribution near 1 GeV
Galaxy cluster shocks (Keshet et al. 2003, Blasi Gabici & Brunetti 2007)

Data: Sreekumar et al. (1998)
Strong, Moskalenko, & Reimer (2000)
Other Evidence for High Energy $\gamma$-Ray Components in Blazars

- Inferring intrinsic spectrum after subtracting out absorption on EBL
- Implied large Doppler factors of TeV blazars
- Orphan TeV flares
- Linear jets

Aharonian et al., Nature, 2005
d \sim 200 \text{ Mpc}

l_{jet} \sim 1 \text{ Mpc} \quad (l_{proj} = 240 \text{ kpc})

Deposition of energy through ultra-high energy neutral beams (Atoyan and Dermer 2003)

Blazars as High Energy Hadron Accelerators

Armen Atoyan (UdeM, Concordia)

---

Powerful blazars (FR-II) with neutrons and γ-rays with energies above 100 PeV and 1 PeV, respectively, contribute to the acceleration process. Neutrons with energies greater than 100 PeV and γ-rays with energies above 1 PeV take away approximately 5-10% of the total WCR (E > 10^{15}eV/1 PeV) injected at R < R_{BLR}. The diagram illustrates the energy flux (E F(E)) as a function of log(E) in eV.
Guaranteed Strong Photohadronic Losses

Do GRBs/blazars have hard photohadronic tails?

\[ \rho_{\phi\pi} > \frac{1 + z}{\delta_D t_v} \]

\[ \rho_{\phi\pi} = \frac{3\hat{\sigma} d_L^2 f_{\epsilon_p k} (1 + z)}{m_e c^4 \delta_D^5 t_v^2 \epsilon_{p k}} \]

\[ S(x) = x^a H(x; x_a, 1) + x^b H(x; 1, x_b) \]

\[ x = \epsilon / \epsilon_{p k} = \epsilon' / \epsilon'_{p k} \]

\[ \tau_{\gamma\gamma} = \frac{\sigma_T}{12\hat{\sigma}} \approx 800 \]

w/ Truong Le (NRL), Enrico Ramirez-Ruiz (UCSC) to be submitted to PRL
### Table of Requirements for Photopion Losses

**TABLE I:** Doppler factor $\delta_{\phi\pi}$ for guaranteed photopion losses, $\gamma$-ray photon energy $E_{\gamma\gamma}$ for $\gamma\gamma$ attenuation with photons at the peak of the target photon SED, and cosmic ray energy $E_{p\pi}^\phi$ for photopion interactions with peak target photons (sources at $z = 2$ except for XBL, at $z \approx 0.08$, $d_L = 10^{27}$ cm).

<table>
<thead>
<tr>
<th>Source</th>
<th>$\ell$</th>
<th>$\eta$</th>
<th>$\tau$</th>
<th>$j$</th>
<th>$\delta_{\phi\pi}$</th>
<th>$E_{\gamma\gamma}$ (GeV)</th>
<th>$E_{p\pi}^\phi$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSRQ</td>
<td>28.7</td>
<td>-11</td>
<td>5</td>
<td>-5 (5 eV)</td>
<td>9</td>
<td>92</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td>IR/optical</td>
<td></td>
<td></td>
<td></td>
<td>-6 (0.5 eV)</td>
<td>16</td>
<td>$30 \times 10^3$</td>
<td>$1.6 \times 10^{19}$</td>
</tr>
<tr>
<td>FSRQ</td>
<td>28.7</td>
<td>-11</td>
<td>5</td>
<td>-2 (5 keV)</td>
<td>1.6</td>
<td>0.03</td>
<td>$1.6 \times 10^{13}$</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>2.8</td>
<td>0.92</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>XBL</td>
<td>27</td>
<td>-10</td>
<td>3</td>
<td>-2 (5 keV)</td>
<td>1.3</td>
<td>0.14</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>2.3</td>
<td>4.7</td>
<td>$9 \times 10^{14}$</td>
</tr>
<tr>
<td>GRB</td>
<td>28.7</td>
<td>-6</td>
<td>0</td>
<td>0 (511 keV)</td>
<td>160</td>
<td>2.9</td>
<td>$2 \times 10^{15}$</td>
</tr>
<tr>
<td>$\gamma$ ray</td>
<td></td>
<td></td>
<td></td>
<td>-1 (51 keV)</td>
<td>280</td>
<td>92</td>
<td>$5 \times 10^{16}$</td>
</tr>
<tr>
<td>X-ray flare</td>
<td>-9</td>
<td>2</td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>50</td>
<td>290</td>
<td>$1.6 \times 10^{17}$</td>
</tr>
</tbody>
</table>
Correlation of Fluxes for FSRQs

Sreekumar et al. (1998) astro-ph/0610195

Synchrotron and IC fluxes from the pair-photon cascade for the Feb 1996 flare of 3C279

(a) FSRQ

$\varepsilon_{pk} = 10^{-5}$

$\gamma\gamma$ opacity

$\tau_{\gamma\gamma}(\varepsilon) \propto \varepsilon^{1-a}$

GLAST LAT

Target Photon SED

Photon loss rate (normalized)

$-2$, $-1$, $b = -1/2$, $a = 1/2$, $a = 1$, $a = 2$

$\log [E \text{ (eV)}]$
### Table of Requirements for Photopion Losses

TABLE I: Doppler factor $\delta_{\phi\pi}$ for guaranteed photopion losses, $\gamma$-ray photon energy $E_{\gamma \gamma}$ for $\gamma\gamma$ attenuation with photons at the peak of the target photon SED, and cosmic ray energy $E_{p\pi}^{\phi\pi}$ for photopion interactions with peak target photons (sources at $z = 2$ except for XBL, at $z \approx 0.08$, $d_L = 10^{27}$ cm).

<table>
<thead>
<tr>
<th></th>
<th>$\ell$</th>
<th>$\eta$</th>
<th>$\tau$</th>
<th>$j$</th>
<th>$\delta_{\phi\pi}$</th>
<th>$E_{\gamma \gamma}$(GeV)</th>
<th>$E_{p\pi}^{\phi\pi}$(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSRQ</td>
<td>28.7</td>
<td>-11</td>
<td>5</td>
<td>-5 (5 eV)</td>
<td>9</td>
<td>92</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td>IR/optical</td>
<td></td>
<td></td>
<td></td>
<td>-6 (0.5 eV)</td>
<td>16</td>
<td>$30 \times 10^3$</td>
<td>$1.6 \times 10^{19}$</td>
</tr>
<tr>
<td>FSRQ</td>
<td>28.7</td>
<td>-11</td>
<td>5</td>
<td>-2 (5 keV)</td>
<td>1.6</td>
<td>0.03</td>
<td>$1.6 \times 10^{13}$</td>
</tr>
<tr>
<td>X–ray</td>
<td></td>
<td></td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>2.8</td>
<td>0.92</td>
<td>$5 \times 10^{14}$</td>
</tr>
<tr>
<td>XBL</td>
<td>27</td>
<td>-10</td>
<td>3</td>
<td>-2 (5 keV)</td>
<td>1.3</td>
<td>0.14</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>X–ray</td>
<td></td>
<td></td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>2.3</td>
<td>4.7</td>
<td>$9 \times 10^{14}$</td>
</tr>
<tr>
<td>GRB</td>
<td>28.7</td>
<td>-6</td>
<td>0</td>
<td>0 (511 keV)</td>
<td>160</td>
<td>2.9</td>
<td>$2 \times 10^{15}$</td>
</tr>
<tr>
<td>$\gamma$ ray</td>
<td></td>
<td></td>
<td></td>
<td>-1 (51 keV)</td>
<td>280</td>
<td>92</td>
<td>$5 \times 10^{16}$</td>
</tr>
<tr>
<td>X–ray flare</td>
<td></td>
<td>-9</td>
<td>2</td>
<td>-3 (0.5 keV)</td>
<td>50</td>
<td>290</td>
<td>$1.6 \times 10^{17}$</td>
</tr>
</tbody>
</table>
Correlation of Photon and Neutrino Fluxes

TABLE I: Doppler factor $\delta_{\phi\pi}$ for guaranteed photopion losses, $\gamma$-ray photon energy $E_{\gamma\gamma}$ for $\gamma\gamma$ attenuation with photons at the peak of the target photon SED, and cosmic ray energy $E_{p}^{\phi\pi}$ for photopion interactions with peak target photons (sources at $z = 2$ except for XBL, at $z \approx 0.08$, $d_{L} = 10^{27}$ cm).

<table>
<thead>
<tr>
<th></th>
<th>$\ell$</th>
<th>$\eta$</th>
<th>$\tau$</th>
<th>$j$</th>
<th>$\delta_{\phi\pi}$</th>
<th>$E_{\gamma\gamma}$ (GeV)</th>
<th>$E_{p}^{\phi\pi}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSRQ</td>
<td>28.7</td>
<td>-11</td>
<td>5</td>
<td>-5</td>
<td>9</td>
<td>92</td>
<td>$5 \times 10^{17}$</td>
</tr>
<tr>
<td>IR/optical</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-6$ (0.5 eV)</td>
<td>16</td>
</tr>
<tr>
<td>FSRQ</td>
<td>28.7</td>
<td>-11</td>
<td>5</td>
<td>-2</td>
<td>1.6</td>
<td>0.03</td>
<td>$1.6 \times 10^{13}$</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>2.8</td>
</tr>
<tr>
<td>XBL</td>
<td>27</td>
<td>-10</td>
<td>3</td>
<td>-2</td>
<td>1.3</td>
<td>0.14</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-3 (0.5 keV)</td>
<td>2.3</td>
</tr>
<tr>
<td>GRB</td>
<td>28.7</td>
<td>-6</td>
<td>0</td>
<td>0</td>
<td>160</td>
<td>2.9</td>
<td>$2 \times 10^{15}$</td>
</tr>
<tr>
<td>$\gamma$ ray</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1 (51 keV)</td>
<td>280</td>
</tr>
<tr>
<td>X-ray flare</td>
<td></td>
<td>-9</td>
<td>2</td>
<td>-3</td>
<td>50</td>
<td>290</td>
<td>$1.6 \times 10^{17}$</td>
</tr>
</tbody>
</table>
Correlation of Fluxes for GRBs

Sreekumar et al. (1998) astro-ph/0610195

Synchrotron and IC fluxes from the pair-photon cascade for the Feb 1996 flare of 3C279

Graph showing the correlation of fluxes for GRBs, with a focus on the Feb 1996 flare of 3C279.
Neutrino Detection from GRBs with Large Baryon-Loading

For a fluence of $3 \times 10^{-4}$ ergs/cm$^2$, (~2/yr)

$N_\nu$ predicted by IceCube:

$N_\nu \approx 1.3$, 0.1, 0.016 for $\delta = 100$, 200, and 300, respectively in collapsar model for $f_{CR} = 20$

Dermer and Atoyan (PRL, 2003)

Nonthermal Baryon Loading Factor $f_b = 20$
Swift GRB Light Curves

photohadronic fluorescence GeV emission

Cosmogenic GZK $\gamma$-Ray Intensity

(Le & Dermer 2006)

Dermer, unpublished calculations, 2007

astro-ph/0611191
every dark matter model makes a prediction for the diffuse γ-ray background
**Neutrinos: expected fluences/numbers**

Expected $\nu$ - fluences calculated for 2 flares, in 3C 279 and Mkn 501; red curves – from internal photons, black & green curves - external component (Atoyan & Dermer 2003).

**Expected numbers of $\nu$ for IceCube - scale detectors, per flare:**

- **3C 279**: $N_\nu = 0.35$ for $\delta = 6$ (solid curve) and $N_\nu = 0.18$ for $\delta = 10$ (dashed)
- **Mkn501**: $N_\nu = 1.2 \times 10^{-5}$ for $\delta = 10$ (solid) and $N_\nu = 10^{-5}$ for $\delta = 25$ (dashed)

('persistent') $\gamma$ -level of 3C279 $\sim 0.1 F_{\gamma} (flare)$, (+ external UV for $p\gamma$)

$\Rightarrow$ $N_\nu \sim$ few- several per year can be expected from poweful HE $\gamma$ blazars.

**N.B.** : all neutrinos are expected at $E >> 10$ TeV

**Detection of one $\nu$ implies large energy in neutrals**

Crucial assumption: same energy injected in protons as observed in radiation modulo Doppler factor $\delta$. 

![Graph showing expected fluences/numbers for 3C 279 and Mkn 501](image-url)
Summary

• GLAST predictions of number and evolution of blazars

• Residual diffuse isotropic $\gamma$-ray background:
  hard blazar emission components?
  new populations of $\gamma$-ray sources?

• Photohadronic cascades make hadronic $\gamma$-ray emission component from FSRQs, not BL Lac objects

• GLAST can detect anomalous $\gamma$-ray emission signatures associated with hadronic acceleration in blazar or GRB jets

• Diffuse emission from cosmogenic $\gamma$-ray, dark matter