Introduction to gamma-ray blazars
Deirdre HORAN
LLR / Ecole Polytechnique
deirdre@llr.in2p3.fr
1. Active galactic nuclei
2. Blazars
3. Models of blazar emission
4. The Fermi blazars
5. The TeV blazars
6. The GeV–TeV Connection
7. The extra-galactic background light
8. Intergalactic magnetic fields
9. Characterising variability
Active galactic nuclei
- 1/9 -
Active Galactic Nuclei

CHARACTERISTICS

* central nucleus outshines the rest of the galaxy
* high luminosity (normally)
* emission across entire spectrum ... radio to keV, MeV, TeV
  ➡ non-thermal
* strong variability
* radio-loud sources:
  ➡ relativistic jets ... superluminal motion
Active Galactic Nuclei

Beckmann & Shrader, astro-ph/1302.1397
Active Galactic Nuclei

(A few % of all galaxies)

Radio-quiet
(85% – 95%)
- Spirals
  - The most common class of AGN
- QSOs
  - Quasi-Stellar Objects

Radio-loud
(5% – 15%)
- Ellipticals
- Fanaroff–Riley Galaxies
- Blazars
  - (< 5% of all AGNs)

Seyfert 1
- Have both broad lines (Balmer, Hydrogen lines) and narrow lines of ionized metals

Seyfert 2
- Show only narrow lines of all species

FR1
- Low luminosity

FR2
- High luminosity

FSRQs
- Flat Spectrum Radio Quasars

BL Lacs
- Feature-less optical spectrum

LSP, ISP, HSP
- LBL, IBL, HBL
- Low, intermediate & high synchrotron peaked

identified as Fermi sources
Active Galactic Nuclei

(A few % of all galaxies)

Radio-quiet
(85% – 95%)
- Spirals
  - The most common class of AGN
  - Seyfert 1
    - Have both broad lines (Balmer, Hydrogen, and ionized metals)
  - Seyfert 2
    - Show only narrow lines of all species

Radio-loud
(5% – 15%)
- QSOs
- Ellipticals
- Blazars
  - (< 5% of all AGNs)

Low, intermediate & high synchrotron peaked

identified as TeV sources

Deirdre HORAN --- 2013 Fermi Summer School --- Lewes, Delaware
Blazars

2/9
Blazars

CHARACTERISTICS

* <5% of all AGN
* jet points "at" us
* flat radio spectrum
* radio loud AGN
* large amplitude variability
* optical polarisation
* spectral energy distribution
Blazars

Superluminal motion

First proposed by Rees in 1966 (Nature, 211, 468) years before it was first observed when VLBI techniques were developed.

First pulse travels to observer in time $D/c$; the second, emitted time $\Delta t$ later, has a shorter distance to travel: $D-\Delta y$.

Difference in arrival time is:

$$\Delta t_{\text{obs}} = \left[\Delta t + \frac{(D-\Delta y)}{c}\right] - \left[\frac{D}{c}\right]$$
Blazars

Superluminal motion

Difference in arrival time is:

\[ \Delta t_{\text{obs}} = \left[ \Delta t + \frac{(D - \Delta y)}{c} \right] - \left[ \frac{D}{c} \right] \]

substitute for \( \Delta y \) & rearrange:

\[ \Delta t_{\text{obs}} = \Delta t \left( 1 - \beta \cos \theta \right) \]

measured transverse velocity, \( v_{\text{obs}} \)

\[ v_{\text{obs}} = \frac{\Delta x}{\Delta t_{\text{obs}}} = \frac{\beta c \sin \theta}{(1 - \beta \cos \theta)} \]

therefore:

\[ \beta_{\text{obs}} = \frac{\beta \sin \theta}{(1 - \beta \cos \theta)} \]
Blazars

Superluminal motion

So, if the plasma velocity was 0.95c and the angle to the observer was 5deg, the apparent velocity would be 1.5c. The effect is maximised when $\cos \theta = \beta$
Blazars

Relativistic beaming

• Another relativistic effect occurs because the knots of plasma are moving at velocities close to that of light
• When an emitting plasma has a bulk relativistic motion relative to a fixed observer, its emission is beamed in the forward direction in the fixed frame
• The flux density is thus changed by relativistic time dilation so an observer sees much more intense emission than if the plasma were at rest
• The observed emission, \( S_{\text{obs}} \) is boosted in energy over that emitted in the rest frame, \( S \)

Definitions:

The Doppler factor is a measure of the strength of the beaming: 

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

The Lorenz factor: 

\[
\Gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad \text{where} \quad \beta = \frac{v}{c}
\]

\[
S_{\text{obs}} = S \left[ \Gamma (1 - \beta \cos \theta) \right]^{-3}
\]

If plasma velocity is 0.95c and \( \theta \) is 5deg, the boosting factor will be \(~198\)
**Blazars**

**Pair-production optical depth**

- High energy gamma rays collide with softer radiation to produce $e^+e^-$ pairs
- For gammas to escape from a source, the optical depth for this process $\tau_e$ must be sufficiently low
- The cross section for this process is maximized for collisions between gamma rays of energy ...

$$X_\gamma = \frac{\hbar \gamma}{mc^2}$$

and target photons of energy ...

$$X_{\text{target}} = \frac{1}{X_\gamma}$$

- The optical depth is then defined as:

$$\tau_{e^+} = \frac{\sigma_T}{5} N X_{\text{target}} R$$

... where $N$ is the number of soft photons, $R$ is the radius of the plasma "blob" (assumed shape) and $\sigma_T$ is the Thompson-scattering cross section*

- A useful parameter that can then be derived** is the compactness of the source - it is a direct measure of the importance of the pair-production process

$$e = \frac{L}{R \sigma_T \text{c}}$$

- The criterion for gammas to escape from a source is ...

$$\tau_{e^+} \sim \frac{e}{\Delta_0} << 1$$

---


**Urry & Padovani (1995) PASP, 107, 803*
Blazars

SPECTRAL ENERGY DISTRIBUTION

power vs. energy
Blazars

SPECTRAL ENERGY DISTRIBUTION

Before, definitions were based on ratio of flux at 5GHz to that at 1 keV
Models of blazar emission

3/9
Models of blazar emission

SPECTRAL ENERGY DISTRIBUTION

power

"synchrotron"

"inverse Compton"

energy
Models of blazar emission

Lower energy emission due to synchrotron emission from relativistic $e^-$s in the jet

Two fundamentally different approaches to explain the higher energy emission

• Leptonic & Hadronic
Models of blazar emission

Lower energy emission due to synchrotron emission from relativistic $e^-$s in the jet

Two fundamentally different approaches to explain the higher energy emission

- Leptonic & Hadronic
  - radiative output dominated by $e^-/e^+$
  - high-energy photons most likely the result of inverse Compton scattering by the same $e^-$s that produced the synch
    - upscatter the low-energy photons responsible for first bump
      - synchrotron self-Compton
    - upscatter photons from the broad-line region, disc, torus ...
      - external Compton
Models of blazar emission

Lower energy emission due to synchrotron emission from relativistic $e^-$s in the jet

Two fundamentally different approaches to explain the higher energy emission

- Leptonic & Hadronic
  - both $e^-/e^+$ and $p$ accelerated to ultra-relativistic energies
  - $p$'s exceed threshold for $p\gamma$ photo-pion production on soft photon field in emission region
  - high energy emission dominated by
    - proton synchrotron
    - $\pi^0$ decay products
    - synchrotron and Compton emission from secondary products of charged pions
    - external Compton

Models of blazar emission

- leptonic models provide good fits to many blazars

Models of blazar emission

- leptonic models provide good fits to many blazars
- X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models


Fortson et al. (2012) Gamma 2012
Models of blazar emission

- leptonic models provide good fits to many blazars
- X-ray and gamma-ray emission often correlated - a fact naturally explained by SSC models
- in hadronic models, the cooling times are longer, which makes it more difficult to explain the rapid variability often seen in blazars
  - proton synchrotron can produce rapid variability with very high energy protons in extremely magnetised, compact regions


Doppler factors of > 100 required

Models of blazar emission


“orphan” flare from TeV blazar, 1ES 1959+650

Hadronic models have been invoked to explain this behaviour.

Sahu et al. (2013), Phys. Rev. D ...
... (in press) astro-ph/1305.4985
Models of blazar emission

- VHE emission discovered by H.E.S.S. (ATel July 2010)
- Hard Fermi spectrum (2.1) and nearby ($z=0.049$)
  ➡ excellent candidate for TeV emission
- X-ray observations taken simultaneously with VHE reveal onset of HE component at unusually low energies for a TeV BL Lac
Models of blazar emission

Extensive Multifrequency Campaigns on the Classical

1 – We do NOT know well how blazars work

2 – Extensive (6 months) campaigns were done in 2010 and are ongoing in 2011 for Mrk421 and Mrk501. This is a multi-instrument and multi-year effort

Similar SED modeling parameters for Mrk421 and Mrk501:

The SED can be described with a 1-zone SSC model with an electron distribution with 2 breaks internal to particle acceleration (20 GeV – 1 TeV)

Correlation of instruments covering different energies needed

We are performing an unprecedentedly long and dense monitoring of the energy distribution parameterized by three power laws with two breaks (in the electron energy distribution) at roughly the temporal and energy coverage of these sources to date. In this conference, we report on some of the results we obtained

Enhanced observational capability can be used to provide a robust test of the models

We do NOT know well how blazars work

at unusually low energies for a TeV BL Lac
Models of blazar emission

VHE emission discovered by H.E.S.S. (ATel July 2010)

- Hard Fermi spectrum (2.1) and nearby (z=0.049)
  ➡ excellent candidate for TeV emission

- X-ray observations taken simultaneously with VHE reveal onset of HE component at unusually low energies for a TeV BL Lac

Difficult to model with a single zone homogeneous SSC model due to the unprecedented width of the HE component compared to the LE component
The Fermi blazars

4/9
The Fermi blazars

1873 sources
1298 identified/associated

84% AGN

Nolan et al. (2012), ApJS, 199, 31

Deirdre HORAN --- 2013 Fermi Summer School --- Lewes, Delaware
The Fermi blazars

   Based on OFG, 3 months data, $\sim$10σ
   106 high-confidence blazars

   Based on 1FGL, 11 months data, $\sim$5σ
   523 (blazars) / 599 (total) in clean sample

   Based on 2FGL, 24 months data, $\sim$5σ
   862 (blazars) / 886 (total) in clean sample

---

FIGURE CREDIT: S. FEGAN

---

Deirdre HORAN -- 2013 Fermi Summer School -- Lewes, Delaware
The Fermi blazars

curve represents the detection limit

ACKERMANN ET. AL 2011, APJ 743, 171
## The Fermi blazars

### Table 5
Census of Sources

<table>
<thead>
<tr>
<th>AGN Type</th>
<th>Entire 2LAC</th>
<th>2LAC Clean Sample$^a$</th>
<th>Low-lat Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>1017</td>
<td>886</td>
<td>104</td>
</tr>
<tr>
<td>FSRQ</td>
<td>360</td>
<td>310</td>
<td>19</td>
</tr>
<tr>
<td>LSP</td>
<td>246</td>
<td>221</td>
<td>7</td>
</tr>
<tr>
<td>ISP</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>HSP</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>No classification</td>
<td>108</td>
<td>86</td>
<td>10</td>
</tr>
<tr>
<td>BL Lac</td>
<td>423</td>
<td>395</td>
<td>16</td>
</tr>
<tr>
<td>LSP</td>
<td>65</td>
<td>61</td>
<td>3</td>
</tr>
<tr>
<td>ISP</td>
<td>82</td>
<td>81</td>
<td>3</td>
</tr>
<tr>
<td>HSP</td>
<td>174</td>
<td>160</td>
<td>5</td>
</tr>
<tr>
<td>No classification</td>
<td>102</td>
<td>93</td>
<td>5</td>
</tr>
<tr>
<td>Blazar of unknown type</td>
<td>204</td>
<td>157</td>
<td>67</td>
</tr>
<tr>
<td>LSP</td>
<td>24</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>ISP</td>
<td>13</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td>HSP</td>
<td>65</td>
<td>53</td>
<td>13</td>
</tr>
<tr>
<td>No classification</td>
<td>102</td>
<td>74</td>
<td>41</td>
</tr>
<tr>
<td>Other AGNs</td>
<td>30</td>
<td>24</td>
<td>2</td>
</tr>
</tbody>
</table>

**Note.** $^a$ Sources with single counterparts and without analysis flags. See Section 5 for the definitions of this sample.

**Figure 18.** Theoretical contribution (W(E) of Equation (A3)) to TS per Ms and per log(E) interval as a function of energy for a power-law source over the average background at $|b| > 10^\circ$. The assumed photon spectral index is 2.2. The dashed line is for an isolated source. The full line includes approximately the effect of source confusion.

*8 misaligned blazars
4 NLSyIls
10 AGN of other type
2 starbursts

**Abdo et al. 2010, ApJS 188, 405**

“If the seed photon source for external Compton scattering is the broad line region (BLR), and the BLR strength is correlated with the power injected into electrons in the jet, one would expect that more luminous jets have stronger broad emission lines and greater Compton cooling, and thus a lower $\nu_{\text{sy}}$. As the power injected in electrons is reduced, the broad line luminosity decreases, there are fewer seed photons for Compton scattering, and consequently the peak synchrotron frequency moves to higher frequencies. This is also reflected in the lower luminosity of the Compton-scattered component relative to the synchrotron component as $\nu_{\text{sy}}$ moves to higher frequencies.”

The Fermi blazars

ACKERMANN ET. AL 2011, APJ 743, 171
The Hard Source List - a catalog above 10 GeV

D. Paneque, Fermi Symposium (2012)

- Work is underway to publish the 1st Fermi-LAT catalog of sources > 10 GeV

- Shape of the spectrum at > 10 GeV might not be well characterized if we use a single fit in the energy range 0.1 GeV – 100 GeV
  - Lower energies have larger statistical weight

- The variability at the highest Fermi-LAT energies could be different from that at the lowest energies, which may radiate from the same/different location
  - Are sources more variable at HE than at LE ? or the other way around ?

- Understand better the population of sources emitting above 10 GeV
  - What are the sources dominating the highest LAT energies?

- Identify promising candidates for IACTs ... new VHE discoveries
The TeV blazars
5/9
The TeV blazars

145 sources
114 identified/associated

84%
AGN*

*95% blazars
The TeV blazars

As of writing this talk, there are 145 sources in TeVCat - 57 Extragalactic

HBLs IBLs LBLs FRIs FSRQs

New TeVCat options coming soon
The TeV blazars

As of writing this talk, there are 145 sources in TeVCat - 57 Extragalactic

Only two sources are not AGN!

Most numerous source class in TeV sky

Most numerous source class in TeV sky
The GeV–TeV Connection
6/9
# The GeV–TeV Connection

<table>
<thead>
<tr>
<th>Source</th>
<th>Total No. Sources</th>
<th>Total No. Identified*</th>
<th>No. AGN</th>
<th>% AGN that are blazars</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeV ... Fermi 2FGL</td>
<td>1873</td>
<td>1298 (69%)</td>
<td>1092 (84%)</td>
<td>74%</td>
</tr>
<tr>
<td>TeV ... TeVCat</td>
<td>145</td>
<td>117 (81%)</td>
<td>55 (47%)</td>
<td>96%</td>
</tr>
</tbody>
</table>

*Identified / Associated

49 of the 55 TeV AGN are in 2FGL
The GeV-TeV Connection

- Analysed 27 months of Fermi data for the TeV AGN that had spectral information available (26 objects)
- Compared the TeV AGN with the AGN from 2FGL
- Computed SEDs for all objects
- The combined GeV-TeV spectra of some blazars (1ES 0229+200, 1ES 0347-121, 1ES 1101-232, 1ES 1218+304, H 1426+428) suggest an inverse-Compton peak beyond 1 TeV
The GeV–TeV Connection

- TeV instruments are pointed and have relatively small fields of view
- Low duty cycles (~10%)
  ➡ Need targets

- Fermi has a very large field of view - sees a fifth of the sky at any given time
- Surveys entire sky every three hours
  ➡ Transients, cataloging

Since Fermi was launched, 29 TeV AGN detected - 14 thanks to LAT data
49 of the 55 TeV AGN are in 2FGL

- At the time of publication, there were 6 TeV AGN that were not detected in 2FGL
- Since then, 8 TeV AGN have been detected - they were all in 2FGL
  ➡ still 6 TeV AGN not in 2FGL
- all HBL
- among the weakest TeV AGN
- 3 have subsequently been reported as detections (non-Fermi pubs)

<table>
<thead>
<tr>
<th>Name</th>
<th>Class</th>
<th>% Crab</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHBL J001355.9-185406</td>
<td>HBL</td>
<td>1.0</td>
</tr>
<tr>
<td>IES 0229+200*</td>
<td>HBL</td>
<td>1.8</td>
</tr>
<tr>
<td>IES 0347-121*</td>
<td>HBL</td>
<td>2.0</td>
</tr>
<tr>
<td>PKS 0548-322*</td>
<td>HBL</td>
<td>1.3</td>
</tr>
<tr>
<td>IES 1312-423</td>
<td>HBL</td>
<td>0.4</td>
</tr>
<tr>
<td>HESS J1943+213</td>
<td>HBL</td>
<td>1.5</td>
</tr>
</tbody>
</table>

*Detections reported in the literature since 2FGL
The extragalactic background light

7/9

Deirdre HORAN -- 2013 Fermi Summer School -- Lewes, Delaware
The further away the object we detect, the more its TeV photons are absorbed by the EBL – this results in a break in the spectrum.

Increasing distance
The extra-galactic background light

The extra-galactic background light

HESS data on seven blazars were used to search for the absorption signature of the EBL - it was detected at 9 sigma - results are only slightly above the lower limits calculated by summing galaxies visible in sky surveys.
Intergalactic magnetic fields
8/9
Intergalactic magnetic fields

- when we detect TeV gamma rays from a distant source, we know that the signal has already been attenuated - only a fraction of those emitted arrive on Earth
- the gamma rays collide with photons of the EBL en route from the source and pair produce

➡️ if there were NO magnetic fields in the universe, these charged pairs would not get deflected, they would travel in original direction until they Compton upscattered an EBL photon to MeV-GeV energies*

- in this way, the original TeV gamma rays get reprocessed to lower energy radiation
- IF we could identify a distant, steady** TeV source which had NO GeV emission, this could be an indication that the B-fields between the source and us deflected the charged pairs such that the reprocessed lower energy emission was "removed" (scattered) from the signal

* the mean free path for e+/e- is low ~kpc  ** if the source is at a lower level now than when the TeV emission that we are detecting was emitted, it could be argued that, since the radiation due to the deflected pairs has longer to travel, it would be delayed by some time - and it hasn't arrived yet
Intergalactic magnetic fields

Place constraints on the intergalactic B-field strength using the direct and cascade components of the GeV-TeV spectrum of 1ES 0229+200


Deirdre HORAN --- 2013 Fermi Summer School --- Lewes, Delaware
Characterising variability
9/9
Characterising variability

Quantifying the variability of blazars

excess variance


\[
\sigma_{\text{rms}}^2 = \frac{\sigma_r^2}{N\mu^2} = \frac{\sum_{i=1}^{N} (X_i - \mu)^2 - \sigma_i^2}{N\mu^2}
\]

N points in each light curve \( X_i \)

\( \mu \) is the unweighted arithmetic mean of the \( X_i \)
Characterising variability

Putting an upper limit on the excess variance

When no (negative) excess variance is measured in the data, we can estimate the level of intrinsic variance that could be present in the lightcurve but that would still allow us to arrive at this value for excess variance.

1. Simulate lightcurves by generating, for each datapoint $F_i \pm dF_i$ (F is the $i$th data point and dF is the $i$th uncertainty, $i=1:N$), a normal distribution centred on the mean of the measured lightcurve with width of $\sqrt{dF_i^2 + \text{VARIANCE}^2}$.

2. For each level of VARIANCE, generate a large number of lightcurves.
Characterising variability

Sample lightcurves for different levels of VARIANCE
Characterising variability

Putting an upper limit on the excess variance

When no (negative) excess variance is measured in the data, we can estimate the level of intrinsic variance that could be present in the lightcurve but that would still allow us to arrive at this value for excess variance.

1. Simulate lightcurves by generating, for each datapoint $F_i \pm dF_i$ ($F$ is the $i$th data point and $dF$ is the $i$th uncertainty, $i = 1:N$), a normal distribution centred on the mean of the measured lightcurve with width of $\sqrt{dF_i^2 + \text{VARIANCE}^2}$.

2. For each level of VARIANCE, generate a large number of lightcurves.

3. Calculate the excess variance for each of these lightcurves and histogram these for each level of VARIANCE.
Characterising variability

Histograms of excess variance for each VARIANCE added
Characterising variability

Putting an upper limit on the excess variance

When no (negative) excess variance is measured in the data, we can estimate the level of intrinsic variance that could be present in the lightcurve but that would still allow us to arrive at this value for excess variance.

1. Simulate lightcurves by generating, for each datapoint $F_i \pm dF_i$ ($F$ is the $i$th data point and $dF$ is the $i$th uncertainty, $i=1:N$), a normal distribution centred on the mean of the measured lightcurve with width of $\sqrt{dF_i^2 + \text{VARIANCE}^2}$.

2. For each level of VARIANCE, generate a large number of lightcurves.

3. Calculate the excess variance for each of these lightcurves and histogram these for each level of VARIANCE.

4. For each VARIANCE level, find the excess variance that 95% (or whatever your required confidence level is) of the excess variances are above.
Characterising variability

Histograms of excess variance for each VARIANCE added
Characterising variability

Putting an upper limit on the excess variance

When no (negative) excess variance is measured in the data, we can estimate the level of intrinsic variance that could be present in the lightcurve but that would still allow us to arrive at this value for excess variance.

1. Simulate lightcurves by generating, for each datapoint $F_i \pm dF_i$ ($F$ is the $i$th data point and $dF$ is the $i$th uncertainty, $i = 1:N$), a normal distribution centred on the mean of the measured lightcurve with width of $\sqrt{dF_i^2 + \text{VARIANCE}^2}$

2. For each level of $\text{VARIANCE}$, generate a large number of lightcurves

3. Calculate the excess variance for each of these lightcurves and histogram these for each level of $\text{VARIANCE}$

4. For each $\text{VARIANCE}$ level, find the excess variance that 95% (or whatever your required confidence level is) of the excess variances are above
Characterising variability

Putting an upper limit on the excess variance

By finding where the measured value of excess variance intersects with the curve generated by the 95% values, we can determine the level of VARIANCE that could be present in the light curve but that would still lead to us getting the measured value 5% of the time or less.
Characterising variability

Note on rate and its uncertainty in Fermi data
Thank you for listening
deirdre@llr.in2p3.fr