High-energy emission from blazars

Foteini Oikonomou 15 July 2020 - Virtual Seminar on Multimessenger Astronomy
Active Galactic Nuclei (AGN)

Most powerful "steady" sources in the Universe ($L \geq 10^{47} \text{ erg/s} > 1000$ bright Galaxies!

They host a SMBH ($10^6 - 10^{10} \text{ M}_\odot$). "Active" as emission $>>$ stars in the galaxy - accretion on to SMBH

Visible to large redshifts ($z > 7.5$) - peak $z \sim 2$ (depends on type)

1% of galaxies active

Broad emission lines reveal rapid bulk rotation

[Spectra from: https://www.open.edu/openlearn/science-maths-technology/introduction-active-galaxies/content-section-2.2.2]
The engine

An efficient way to produce the power required, is through accretion onto a black-hole. As much as 10% of the rest mass energy in-falling into a black hole is converted into radiation

\[ L_{\text{disk}} = 0.1 \dot{M}c^2 = 10^{46} \text{ erg/s} \]

In solar masses per year, the requirement is

\[ \dot{M} = \frac{L_{\text{disk}}}{0.1c^2} = 1.75 \frac{L_{\text{disk}}}{10^{46} \text{ erg/s}} M_{\odot} \text{ yr}^{-1} \]

This should be “easy” to supply. A typical galaxy might have gas mass,

\[ M_{\text{gas}} \sim 10^{10} M_{\odot} \]

\[ *1 \text{ erg} \sim 1 \text{ TeV}, L_{\sun} = 3.85 \times 10^{33} \text{ erg/s} \]
The engine

But to provide \(10^{46}\) erg/s, we need a SMBH due to the Eddington limit!

\[
L_{\text{Edd}} = \frac{4\pi G M_m c}{\sigma_T} = 10^{38}\text{erg/s} \left(\frac{M}{M_{\text{Sun}}}\right)
\]

I.e. we need,

\[
M \geq 10^8 M_{\text{Sun}} \left(\frac{L_{\text{disk}}}{10^{46}\text{ erg/s}}\right)
\]
AGN unification

The majority of AGN classes can be explained by three parameters:

- Orientation
- Presence of jet or not (10% have it)
- Radiative efficiency

<table>
<thead>
<tr>
<th>Jetted (radio-loud)</th>
<th>Face on</th>
<th>Side-view</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blazars (BL Lac/FSRQ)</td>
<td>Radio-Galaxies (FRI/II)</td>
<td></td>
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<tr>
<td>Non-jetted (radio-quiet)</td>
<td>Seyfert I</td>
<td>Seyfert II</td>
</tr>
</tbody>
</table>

see Urry & Padovani 1995
10% of AGN have jets

Radio Galaxy 3C272.1 = M84
VLA 6cm image
Copyright (c) NRAO/AUI 2006

Radio galaxy Cygnus A Image credits: NRAO/AUI, A. Bridle
Blazars: star-like appearance

No spectacular jets…but wealth of information from timing/variability and spectra!
Usual relativity (rulers and clocks)

\[ \Delta x = \frac{\Delta x'}{\Gamma} \]

\[ \Delta t = \Delta t' \Gamma \]

\[ \Gamma = \frac{1}{\sqrt{1 - \beta^2}} \]

Not so for photons!
(Terrel 1959)
Relativistic beaming

If the emitting region is moving relativistically, observed features appear boosted:

Doppler factor, \( \delta = \frac{1}{\Gamma(1 - \beta \cos \theta)} \)

\[ (\frac{1}{\Gamma}: \text{Usual special relativity term, } \frac{1}{(1 - \beta \cos \theta)}: \text{Usual Doppler effect.}) \]

\[ \Delta t = \Delta t'/\delta \quad \text{(shortening of timescales)} \]

\[ \Delta x = \Delta x' \delta \]

\[ \nu = \delta \nu', E = \delta E' \quad \text{(blueshift)} \]

\[ L_{\text{obs}} = \delta^4 L' \]

(dashes denote rest-frame quantities)

Special cases:

\[ \delta_{\text{max}} = \delta(0^\circ) = \frac{1}{\Gamma(1 - \beta)} = \Gamma(1 + \beta) \sim 2\Gamma \]

\[ \delta_{\text{min}} = \delta(90^\circ) = 1/\Gamma - \text{recover special relativity} \]

\[ \theta = 1/\Gamma, \cos \theta \approx 1 - \frac{\theta^2}{2} \approx \beta, \delta = \Gamma - \text{opposite of special relativity!} \]
Blazars Dominate the Extragalactic $\gamma$-ray sky

$>90\%$ of extragalactic Fermi sources (see also TeVCaT)
Blazars Dominate the Extragalactic $\gamma$-ray sky

50+ TeV blazars (TeVCat)
2800+ in GeV [4LAC, Fermi Coll 2019]
Blazar Spectral Energy Distribution

PKS 2155–304

Extremely variable!
Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

<table>
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<tr>
<th></th>
<th>BL Lacs</th>
<th>FSRQs</th>
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<tr>
<td>accretion</td>
<td>inefficient</td>
<td>efficient</td>
</tr>
<tr>
<td>EW</td>
<td>&lt; 5 Å</td>
<td>&gt; 5 Å</td>
</tr>
<tr>
<td>$L/L_{\text{Edd}}$</td>
<td>≲ 0.01</td>
<td>≳ 0.01</td>
</tr>
<tr>
<td>$\nu^S_{\text{peak}}$</td>
<td>any</td>
<td>≲ $10^{14}$ Hz</td>
</tr>
</tbody>
</table>
Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

BL Lac

FSRQ

Optical light

Ghisellini 2009
Blazar Classes: BL Lac Objects and Flat Spectrum Radio Quasars

Heckman & Best 2014

BL Lac/FRI

FSRQ/FRII
Classification of BL Lac objects

Emission from BL Lac Objects

$\nu_s = 3 \times 10^6 B \gamma_B^2 \delta$

$\alpha_1 = \frac{n_1 - 1}{2}$

Relativistic electrons in a “blob”

Log $N(\gamma)$

Log $\nu L(\nu)$

Log $\nu$ [Hz]

Log $\nu F_\nu$ [erg cm$^{-2}$ s$^{-1}$]

Image credit: L. Costamante 2011, H. Bradt

“ Astrophysical processes” 2008

see e.g. Tavecchio, Maraschi & Ghisellini 1998
Emission from BL Lac Objects

In this synchrotron + synchrotron self Compton (SSC) model, we can in principle determine the magnetic field strength, doppler factor, γ_b, n_1, n_2, electron density, size of emitting region from observed quantities (see back-up)

Image credit: L. Costamante 2011, H. Bradt
"Astrophysical processes" 2008
Emission from Flat Spectrum Radio Quasars

- 10% of AGN have jets
- UHECR/Neutrino arrival direction correlations
- Emission from Flat Spectrum Radio Quasars

Ghisellini 2009

- Broad line region
- Dust Torus

- Synchrotron
- Inverse Compton

Log $N(\gamma)$

Log $\nu L(\nu)$

Log $\nu [\text{Hz}]$

Log $\nu F_\nu [\text{erg cm}^{-2}\text{s}^{-1}]$

Ghisellini 2009

- $z=0.213$
- disk
- EC
- Syn
- torus
- Corona
- SSC
- EC
Enter the protons

For characteristic values of $B$, $R$, and delta, we end up with $E_{\text{max}}$ in the UHECR ball park,

$$E_{\text{CR, max}} \sim \left( \frac{Z}{1} \right) \left( \frac{\eta}{1} \right) \left( \frac{B}{0.35 \text{ G}} \right) \left( \frac{R'}{10^{16} \text{ cm}} \right) \left( \frac{\Gamma}{25} \right) \sim Z \cdot 5 \times 10^{19} \text{ eV}$$

Hillas criterion

\[ E_{\text{max}} \sim \beta_s h ZRB \Gamma \]

- Neutron stars
- Magnetars
- GRBs
- Starbursts
- Wolf-Rayet stars
- AGN Knots
- AGN Hotspots
- AGN Lobes
- Normal galaxies
- SNe
- Galactic clusters

\[ \begin{align*}
1 \text{ au} & \quad 1 \text{ pc} & \quad 1 \text{ kpc} & \quad 1 \text{ Mpc} \\
\beta = 1.0 & \quad \beta = 0.01
\end{align*} \]
Galactic UHECRs reaccelerated by AGN Jets can fit the UHECR spectrum and composition

Kimura, Murase, Zhang, PRD 97, 023026, 2018
[see also Rodrigues, Heinze, Palladino arXiv:2003.08392]
Clues from UHECR arrival directions

3.9σ excess (post-trial)
of CRs in the direction of Cen A (28 degree radius)
above 37 EeV

3.1σ excess (post-trial)
of CRs in the direction of 33 3FHL AGN (Cen A, Fornax A, M87, Mrk 421...),
14 degree smearing angle
above 39 EeV - but less significant than
starbursts and large-scale structure

*1 EeV = 10^{18} eV
Neutrino production in blazars

Accretion disk

3/8ths of proton energy lost → neutrinos
rest (5/8ths) to photons (gamma-rays/X-rays)

\[ p + γ \rightarrow n + π^+ \rightarrow n + μ^+ν_μ \rightarrow n + e^+ + ν_e + ¯ν_e + ν_μ \]

\[ p + γ \rightarrow p + π^0 \rightarrow p + γ + γ \]

\[ p_{PeV} + γ \rightarrow p + e^+ + e^- \text{ → cascade that peaks in keV band} \]

\[ ⟨E_ν⟩ = \frac{1}{20}E_p \]

\[ ⟨E_γ⟩ = \frac{1}{10}E_p \]

Easy for blazars to produce 20 PeV protons

Image by K. Murase
Constraints on the contribution of blazars to the diffuse neutrino flux: Stacking

\[ \gamma - \text{rays} \quad \text{neutrinos} \quad \text{UHECRs} \]

\[ E^2 \Phi \text{[GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

\[ 10^1 \quad 10^3 \quad 10^5 \quad 10^7 \quad 10^9 \quad 10^{11} \]

+ IceCube HESE, \( \nu_\mu \) 6yr
- IceCube EHE 9yr
- Auger 2017
- Fermi EGB
- KASCADE
- Auger
- TA

* \( \approx 27\% \) with spectral templates Huber; Krings for IceCube Coll PoS (ICRC2017) 994
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Max. 3FHL blazar contribution 16.7%*

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Batista et al, MIAPP UHECR Review, 2019, FrASS, 6, 23
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* clustering limits are sensitive up to ~100 TeV
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Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

* clustering limits are sensitive up to \( \sim 100 \text{ TeV} \)
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

Absence of multiplets implies that the number density is low enough that no source exists at distance low enough to produce a multiplet.
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

autocorrelations (IceCube Coll 2015,17, Ando et al 2017, Dekker & Ando 2019),
EHE Limits (IceCube Coll 2016,17),
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

- Low luminosity AGN
- Starburst galaxies
- Non-jetted AGN
- Galaxy Clusters
- Low luminosity BL Lacs (HSPs)
- Jetted AGN
- Low luminosity Blazars (BL Lacs)
- High luminosity Blazars (FSRQs)

**Muon Neutrino Constraints**

**IceCube Line**

Murase & Waxman 16, PRD 94 (2016) 103006


(UHECR/Neutrino arrival direction correlations)
Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering

autocorrelations (IceCube Coll 2015,17, Ando et al 2017, Dekker & Ando 2019),
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Log(Number density [Mpc$^{-3}$]) vs Log(Neutrino Luminosity[erg/s])

Low luminosity AGN
Starburst galaxies
Non-jetted AGN
Jetted AGN

Muon Neutrino Constraints

IceCube Line

Palladino, Van Vliet et al. 2020, 90% CL no multiplets steady, negative evolution

Low luminosity BL Lacs (HSPs)
Low luminosity Blazars (BL Lacs)
High Luminosity Blazars (FSRQs)

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IceCube Line
Point Source Limits (IceCube)

N_{CR} = 43, N_s = 3

Muon Neutrino Constraints

Low luminosity AGN
Starburst galaxies
Non-jetted AGN
Jetted AGN
Galaxy Clusters
Low luminosity Blazars
High luminosity Blazars

log(Number density [Mpc^{-3}])

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log(Number density [Mpc^{-3}])

log(Neutrino Luminosity[erg/s])

Low luminosity AGN
Starburst galaxies
Non-jetted AGN
Jetted AGN
Galaxy Clusters
High luminosity Blazars

UHECR/Neutrino arrival direction correlations

Constraints on the contribution of blazars to the diffuse neutrino flux: Clustering
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For joint UHECR-neutrino analyses see also ANTARES, IceCube, Auger, Telescope Array 2019 PoS(ICRC2019) 1177,
Resconi et al. MNRAS 468, 1 2017
Blazar flares: Interesting as neutrino point sources

Image from Biteau, Prandini, Costamante+ Nat. Astr 4, 124–131 (2020)
IceCube archival search: $13\pm5$ more neutrinos found in 2014-15

Background fluctuation? Chance probability 0.05%
Neutrino production in TXS 0506+056 in 2017

Other more exotic options find increased neutrino flux:
- hadro-nuclear interactions: Liu, Wang, Xue, Taylor et al, PRD 2019

\[ N_{\nu} \lesssim 0.01/6 \text{ months} \]

\[ \epsilon \lesssim 10^{13} \quad \text{eV} \]

\[ \epsilon \text{F}_\nu \lesssim 10^{12} \quad \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \]
Neutrino production in TXS 0506+056 in 2017

$p_{\text{PeV}} + \gamma \rightarrow p + e^+ + e^- \rightarrow \text{cascade that peaks in keV band}$

3/8ths of proton energy lost $\rightarrow$ neutrinos
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3HSP J095507.9+355101 - IC 200107A


Extreme HSP with luminosity similar to TXS 0506+056 coincident with 0.33+2.23−0.27 PeV track
Redshift = 0.57 (Paiano et al, MNRASL 2020)

See also Giommi, Glauch, Padovani, Resconi, Turcati, Chang MNRAS 2020 who find a 3.23σ excess of IceCube tracks in the direction of HSP/ISP blazars
High-energy neutrinos from other blazar flares?

Optimistic scenario based on 2017 flare of TXS 0506+056

Based on optimistic modelling of TXS 0506+056,
Extended external (sheath) field, Proton luminosity ~ 0.2 - 30 x Eddington

ΔT = 84 days

ΔT = 14 days

ΔT = 13 days

ΔT = 30 days

ΔT = 46 + 84 days

ΔT = 21 days

ΔT = 14 days

ΔT = 28 days

ΔT = 7 days

ΔT = 21 days

ΔT = 7 days

ΔT = 175 days
Expected neutrino signal in optimistic case
Expected neutrino signal in optimistic case

Sum over all flares (~10 years)
Expected neutrino signal with next generation detectors
Outlook

Blazars are fantastic objects

• future multi-wavelength observations will reveal more details of the physical conditions
• ...and about their multi-messenger role