Photons and neutrinos from AGNs

A review on hadronic radiative models

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Blazar: radio-loud AGN whose relativistic jet points towards the observer

Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

Flat-spectrum-radio-quasars: optical/UV spectrum with broad emission lines
BL Lacertae objects: featureless optical/UV spectrum
Spectral energy distributions (SED): two distinct radiative components

FSRQs show a peak in the IR

BL Lacs are classified into:

- IR peak: low-frequency peaked (LBLs)
- optical peak: intermediate (IBLs)
- UV/X peak: high (HBLs)

Fossati et al. 1998
The low-energy SED component is synchrotron emission by electrons

High-energy emission?

Leptonic models: inverse Compton

Same leptons that radiate synchrotron
+ their own synchrotron photons (SSC)
+ external photon fields (EIC)

State-of-the-art models:
- HBLs ➔ SSC
- LBLs / FSRQs ➔ EIC
BLAZARS HADRONIC EMISSION MODELS
Why hadronic models if leptonic ones work?
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- Natural link with neutrinos and cosmic rays: AGNs are candidates for (UHE)CR acceleration
Why hadronic models if leptonic ones work?

- Natural link with neutrinos and cosmic rays: AGNs are candidates for (UHE)CR acceleration

- Leptonic models don’t always work well: Orphan flares!
Simplest hadronic model:
The high-energy component is **proton synchrotron radiation**

(Mannheim 1993, Aharonian 2000, Mucke & Protheroe 2001)
Proton-photon interactions complicate the modeling

\[ p + \gamma = n^0 \pi^0 + n^+ \pi^+ + n^- \pi^- + \ldots \]

\[ 2 \gamma \rightarrow \mu^\pm + \nu_\mu \rightarrow e^\pm + \nu_\mu + \bar{\nu}_\mu + \nu_e \]

Bethe-Heitler pair production

\[ p + \gamma = p' + e^+ + e^- \]

Injection of secondary leptons in the emitting region, triggering synchrotron supported pair-cascades

Synchrotron emission by muons can be important
Leptonic and hadronic models can both work!
Example for Mrk 421 in 2011

Abdo et al. 2011
Why is Bethe-Heitler important?
Injection of pairs at lower energy (compared to photo-meson)
Can dominate the X-ray band and fill the SED valley

Petropoulou and Mastichiadis 2015
Why are muons important?
In some parts of the parameter space we can have a steady state muon population that can radiate in the TeV band

Abdo et al. 2011
Proton-proton interactions

- Can also pion produce and lead to photon and neutrino emission (widely used in Galactic sources, like SNR)

- The required density of target protons is much higher than the one usually assumed in blazar jets
  
  -> can become an important process only in very small and dense emitting regions;

  -> an interesting scenario are the jet-obstacles interactions
FSRQ modeling

Leptonic (EIC)

Hadronic (proton synchrotron)

Hadronic models fit the SED but require super-Eddington luminosities (sometimes by orders of magnitudes -> always check energetics of hadronic models)

\[ L_{jet} = 10^{47-49} \text{ erg/s} \]

Böttcher et al. 2013

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Extreme blazars (peak > 1 keV)

Leptonic modeling faces difficulties (high Doppler factor / high minimum energy of the particle distribution)

Hadronic modeling perfectly suited for them

Cerruti et al. 2015
IceCube-170922A / TXS 0506+056

Most significant association (3σ) of a high-energy (290 TeV) neutrino with an astrophysical source
Proton synchrotron solutions exist, but the expected neutrino rate is very low

\[ \nu \approx 10^{-5} \text{ yr}^{-1} \]

Keivani et al. 2018

\( \nu = 10^{-5} - 10^{-3} \text{ yr}^{-1} \)

Cerruti et al. 2019

Proton synchrotron solutions exist, but the expected neutrino rate is very low

Gao et al. 2018
Lepto-hadronic solutions

They can work: neutrino rates of the order of 0.1 / yr
But rather high energetic requirement : $L_{\text{jet}} \gg L_{\text{Edd}} \simeq \times 10^{46-47} \text{ erg/s}$

$L_{\text{jet}} = (9 - 60) \times 10^{47} \text{ erg/s}$
$v = 0.01 - 0.06 \text{ yr}^{-1}$

$L_{\text{jet}} \simeq \times 10^{50} \text{ erg/s}$
$v = 0.3 \text{ yr}^{-1}$

Cerruti et al. 2019
Gao et al. 2018
Proton-photon interaction on external photon fields

Keivani et al. 2018

\[ L_{jet} = (4 - 150) \times 10^{45} \text{ erg/s} \]
\[ \nu_{\text{max}} = 0.02 \text{ yr}^{-1} \]

Righi et al. 2019

\[ L_{\text{jet}} = 6.3 \times 10^{45} \text{ erg/s} \]
\[ \nu = 0.14 \text{ yr}^{-1} \]

Keivani et al. 2018

\[ L_{\text{jet}} = (3 - 8) \times 10^{45} \text{ erg/s} \]
\[ \nu = 0.12 - 0.34 \text{ yr}^{-1} \]
Alternative hadronic scenario
Jet - cloud interaction

\[ p + p = n^0 \pi^0 + n^+ \pi^+ + n^- \pi^- \]

*Barkov et al. 2012*
$p + p = n^0\pi^0 + n^+\pi^+ + n^-\pi^-$

Alternative hadronic scenario
Jet - cloud interaction

$L_{jet} = 1 \times 10^{48} \text{erg/s}$
$\nu = 0.13 - 0.46 \text{ yr}^{-1}$

see as well Wang et al. 2018

$L_{jet} = (0.8 - 5) \times 10^{46} \text{erg/s}$
$\nu = 0.26 \text{ yr}^{-1}$

see as well Liu et al. 2019
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- **Pure hadronic solutions are excluded!**

- The favored scenario is a **leptonic** electromagnetic emission, with subdominant hadronic component

- Simple one-zone models can be enough, at the expenses of a high proton luminosity, and only if the acceleration efficiency is low
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- External fields as photon target can help on this aspect
Can AGNs accelerate (UHE)CRs?

- From Cerruti et al. 2019, \( E_{p,\text{max}} = (2 - 7) \times 10^{18}\text{eV} \)

- From Ansoldi et al. 2018, \( E_{p,\text{max}} = 2 \times 10^{15} - 2 \times 10^{19}\text{eV} \)

- From Keivani et al. 2018, “assuming the IceCube-170922A association holds, TXS 0506+056 is not a significant UHECR accelerator”

- From Gao et al. 2018, “The scenario [of UHECR in the source] is not acceptable”

TXS0506+056 not really an UHECR accelerator!
Detection of a second neutrino flare in 2014-2015 (without a gamma-ray counterpart)

3.5σ evidence for neutrino emission in 2014-2015 independent from the 2017 event
TXS 0506+056: THE 2014 $\nu$ FLARE

Rodrigues et al. 2019

External field models

Petropoulou et al. 2020

1-zone models

Xue et al. 2021

On corona photons
TXS 0506+056: THE 2014 $\nu$ FLARE

Synchrotron cascades (normalized to get right $\nu$)

Reimer et al. 2019

Compton cascades (on external field!)

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Two-zone model:

- neutrons escape the blazar zone

- proton-photon interaction with external fields at larger scales in the jet

- secondary pairs are isotropized in the larger-scale jet
- **Single zone models are disfavored**: very difficult to get no photons with the neutrino flare (although there may be some room in the MeV band)

- A simple solution could be a two-zone models: the $\nu$ and the $\gamma$-ray emitting region are not the same one.
Developed as an alternative to leptonic models, hadronic models can describe blazar SEDs and provide natural link with *neutrino astronomy* and *cosmic rays physics*

The first (evidence of) neutrino emission from a blazar seems to support *hybrid scenarios*, with sub-dominant hadronic cascades

The 2014-15 neutrino flare of TXS 0506+056 seems to support multi-zone scenarios with neutrino emitting region opaque to gamma-rays
Why is TXS 0506+056 the first neutrino AGN candidate?

Can we get a consistent picture for both 2014/15 and 2017 flares from TXS 0506+056?

Are there leptonic blazars and hadronic blazars?

Are there leptonic flares and hadronic flares?