Cosmic rays, Photons and Neutrinos from Quasars

or

A how-to guide on blazar hadronic models

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The knee, $E \sim 1$ PeV

The ankle, $E \sim 1$ EeV

$E_{\text{Max}?} \sim 100$ EeV?

From Hillas, 2006

From quasars

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CR-\(\gamma\)-\(\nu\) from quasars
COSMIC RAYS

Anisotropy for \(E > 10^{19}\) eV (Auger + TA)

Dipole amplitude : 7 – 13%
Quadrupole : 7 – 10%

99% C.L. upper limit

Fukushima 2015
Sky Plot of SD 5-year Data

- 72 events without array border cut (\(\Delta E/E \sim 20\%\), ang. res. \(\sim 1.7^\circ\))

→ Make over-sampling with 20° radius circle
Why multi-messenger?

The basic process is pion production:

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

Or

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

And then pions decay \( \rightarrow \) photons, leptons and neutrinos!
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\(\gamma - CR - \nu\) studies!

And then pions decay \(\rightarrow\) photons, leptons and neutrinos!
COSMIC RAYS & MULTI-MESSENGER

We now have IceCube observations of astrophysical neutrinos.
**COSMIC RAYS & MULTI-MESSENGER**

PeVatron candidate: Sagittarius A*$^*$

- Gamma-ray emission from SgrA*: cut-off at $\sim 10$ TeV;
- Diffuse emission extending above
- Proposed scenario: emission from CR diffusing away from the black hole with $E_{\text{Max}} \sim 3$ PeV

![Graph showing gamma-ray flux vs energy](image-url)

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CR-$\gamma$-$\nu$ from quasars
Cosmic rays at higher energies are more likely extragalactic, and active galactic nuclei (AGN) are the best candidates.

Indeed the $\gamma$-ray extragalactic sky is full of AGN, and in particular of blazars.
BLAZARS

Blazar: radio-loud AGN whose relativistic jet points in the direction of the observer

→ emission from the jet dominates over any other AGN component (the disk, the BLR, the X-ray corona,...)

→ non-thermal emission from radio to gamma-rays, and extreme variability

- Flat-Spectrum-Radio-Quasars: optical spectrum with broad emission lines
- BL Lacertae objects: optical spectrum featureless
BLAZARS

Spectral energy distribution (SED) two distinct components

FSRQs show, generally, a peak in IR,

BL Lac objects are classified in:

• peak in optical : Low-frequency peaked (LBLs)
• peak en UV/X : High-frequency peaked (HBLs)
• peak >10 KeV : Ultra-high-frequency peaked (UHBLs)

Fossati et al. 1998
BLAZAR LEPTONIC MODELS

- First spectral component
  → Synchrotron emission by relativistic electrons

- Second spectral component:
  inverse Compton scattering
  → for HBLs, the dominant radiation field is the synchrotron emission by $e^\pm$

(Synchrotron-Self-Compton model, SSC)
BLAZAR LEPTONIC MODELS

- First spectral component
  → Synchrotron emission by relativistic electrons

- Second spectral component:
  inverse Compton scattering
  → for FSRQs and LBLs, the dominant field is external (BLR, the disk, the torus)

(External-Inverse-Compton, EIC)
BLAZAR HADRONIC MODELS

- First spectral component remains the same!

→ Synchrotron emission by relativistic electrons

- Second spectral component:

hadronic processes:
→ synchrotron emission by protons
→ secondary particles from p-gamma interactions
LeHa : SIMULATING BLAZAR SEDs

A how-to guide to hadronic blazar models

1) The starting point is a leptonic code (Katarzynski et al. 2001) which simulates the synchrotron and SSC emission from a blazar

Key ingredients :

- synchrotron radiation
- inverse Compton radiation
- absorption by pair-production ($\gamma + \gamma \rightarrow e^+ + e^-$)

What we added :
- improvement in the emissivity calculation (better and faster);
- estimation of the injected secondary pairs (will be important later in the hadronic part), whose stationary state is estimated computing radiative cooling
2) Adding protons in the emitting region

- synchrotron radiation by protons is easy (just replace the mass value)

- proton-photon interactions are complex, and have been implemented using the numerical code SOPHIA (Mucke et al. 2001)

- secondary leptons from p-gamma interactions radiate, and the emission is energetic enough to pair-produce again

→ development of a synchrotron-supported pair-cascade

This is computed iteratively (for our applications, in general the cascade converges after 5 generations)
LeHa : SIMULATING BLAZAR SEDs

A how-to guide to hadronic blazar models

2) Adding protons in the emitting region

- Muons are produced in the pion decay, and if the magnetic field is important they can radiate before decaying to electrons/positrons

  → Muon spectrum extracted from SOPHIA, cooled, and made radiate

- Synchrotron losses by all non-stable particles taken into account

- Bethe-Heitler pair-production : \( p + \gamma \rightarrow e^+ + e^- \)
  This process is not included in SOPHIA, and is computed analytically
LeHa : SIMULATING BLAZAR SEDs

Free parameters of the model:

Emitting region:
- Doppler factor $\delta$
- Magnetic field $B$
- Radius $R$

Electron energy distribution: (broken power-law)
- Spectral indices $n_{e,1}$, $n_{e,2}$
- Minimum, Break, Maximum Energy
- Normalization factor

Proton energy distribution: (broken power-law)
- Spectral indices $n_{p,1}$, $n_{p,2}$
- Minimum, Break, Maximum Energy
- Normalization factor
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Synchrotron cooling of leptons

Injection function is a powerlaw
Injection function is the realistic one (numerical) from pair absorption
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Cascade spectra

Muon stationary distribution

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Known limitations of blazar hadronic models

- We focus on stationary SEDs but blazar are variable, and minute-scale variability is difficult to be achieved with hadrons (due to the longer cooling time-scale)

- Hadronic jets are heavier, and require much higher energies than leptonic ones. In some cases, the required energy budget is (very)super-Eddington, and difficult to be sustained
LeHa : SIMULATING BLAZAR SEDs

First example : application to the HBL Mrk 421

$E_{\text{max, } p} = 10^{18}$ eV

Cerruti et al. 2015
LeHa : SIMULATING BLAZAR SEDs

Comparison of acceleration and cooling time-scales (used to link $E_{\text{Max}}$, $\gamma$, $p$ to $B$)
ULTRA-HIGH-FREQUENCY BL LACs

Peculiar class of blazars, characterized by:

- peak of the synchrotron component at several KeVs, or above (i.e. unconstrained by current telescopes)
- peak of the gamma-ray component at several TeVs, or above (i.e. unconstrained by current telescopes)
- the monitoring of these sources during the last years show that they are not much variable, without rapid flares
- leptonic modeling of these sources results in „unusual“ parameters, such as a high value for $\delta$, and a very compact electron distribution
ULTRA-HIGH-FREQUENCY BL LACs

Hadronic modeling of RGB J0710+591

Proton-synchrotron scenario

$E_{\text{max}, p} \leq 10^{19}$ eV

Lepto-hadronic scenario

$E_{\text{max}, p} \leq 10^{17}$ eV

$\delta = 30$

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ULTRA-HIGH-FREQUENCY BL LACs

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ULTRA-HIGH-FREQUENCY BL LACs

\[ \tau_{ad} < \tau_{syn} \]

\[ \tau_{syn} < \tau_{ad} \]

Eddington luminosity

\[ \frac{u_p + u_e}{u_B} \]

\[ \text{Log}(L \text{ erg/s}) \]

\[ \text{Log}(B \text{ [G]}) \]
Conclusions:

for this peculiar blazar subclass, hadronic models represent a viable alternative to leptonic ones, and they may be even preferred

• not unusual value for $\delta$
• not unusual particle population
• don't violate the energetic
PKS 1424+240

Discovered by VERITAS as a „vanilla“ HBL in 2009

- In 2013 the redshift was estimated to be $z \geq 0.6$ from intergalactic absorption lines
- In 2015 a study of nearby galaxy suggested that the blazar belongs to a cluster at $z = 0.6$
  
  → It is currently the most distant persistent very-high-energy emitter seen with Cherenkov telescopes

(The Universe is opaque to TeV photons due to pair-production over the extragalactic background light)
Assuming $z=0.6$, this is how it looks the „blazar sequence“

$\rightarrow$ It is a rare example of bright HBL

Cerruti et al., In prep.
SSC modeling of PKS 1424+240: very disfavoured. Delta is > 200, and all models are systematically softer in the VHE band.
Hadronic modeling of PKS 1424+240
The pair-cascades produce a natural hardening in the TeV regime
(In this case the model is not EBL absorbed)
Similarly to UHBLs, we have a source which is not satisfactorily described by a simple leptonic model.

→ A hadronic model is a viable solution!

N.B.
In this case other options are investigated:
- multi-zone leptonic models
- EIC models
- cascades in the line of sight
THE CHERENKOV TELESCOPE ARRAY

Cherenkov Telescope Array (CTA): the next-generation telescope at very-high-energies

- Two open observatories, in Chile and Spain
- Array with small/medium/large-size telescopes
- Overall sensitivity a factor of ~10 better than current telescopes
- $E_{\text{threshold}} < 100$ GeV (i.e. overlap with Fermi)
Will CTA be able to detect hadronic signatures?

The focus is in particular on the “cascade bump“:

- hadronic fit to two bright HBLs, Markarian 421 and PKS 2155-304
- systematic study of the parameter space
- simulation of CTA spectra and comparison with simulated leptonic models
Two different hadronic models of PKS 2155-304, showing the emergence of the cascade bump.

Zech, MC, Mazin, 2016, submitted
Simulated CTA spectra for the hadronic and leptonic scenario
Detectability of the cascade bump estimated by fitting the CTA spectrum with a log-parabolic model and comparing leptonic and hadronic results.
THE CHERENKOV TELESCOPE ARRAY

For nearby HBLs, observed in low flux state, CTA will be able to discriminate between (part of the) hadronic models and leptonic models integrating between 50 and 100 hours of observations.

- If the hardening is detected, we will still need to be sure that this is the 'cascade bump', and not some other effect (external photon field? Propagation effects?)
- If the hardening is NOT detected, we will effectively exclude a large part of the hadronic model parameter space.
THE GAMMA-NEUTRINO CONNECTION

Same model as before:

associated neutrino flux, and comparison with IceCube sensitivity to point-like sources

→ still too faint (for the low-state)

Cerruti et al. 2016
THE GAMMA-NEUTRINO CONNECTION

Solutions for the radio-galaxy Centaurus A, a misaligned blazar

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CR-γ-ν from quasars
THE GAMMA-NEUTRINO CONNECTION

Solutions for the HBL PG 1553+113

→ the most optimistic scenario for neutrinos is the lepto-hadronic

But at least part of the parameter space (the denser regions) may be excluded already, because it would overproduce neutrinos
The neutrino spectra vary a lot as a function of the parameter space

- Proton synchrotron scenario in general don't produce a significant amount of neutrinos
  - the peak frequency depends mainly on the maximum proton energy

- Lepto-hadronic models are much more favorable (although the peak frequency is always at higher energies than IceCube sensitivity)
  In some cases even too much favorable
CONCLUSIONS

Blazar hadronic models are a viable scenario to fit the electromagnetic emission from gamma-ray AGNs

- If we detect a clear hadronic signature, it would be the smoking gun for hadron acceleration in AGN
- The best case scenario would be in the near future a flare from a nearby blazar, with simultaneous detection of gammas and neutrinos

→ Future working path is the development of time-dependent hadronic codes
THANKS!