Short Course on High Energy Astrophysics
“Exploring the Nonthermal Universe
with High Energy Gamma Rays”

Lecture 6: Extragalactic Sources of VHE Gamma Rays

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potential extragalactic gamma-ray sources

- Normal Galaxies (nearby, within a few Mpc)
- Starburst Galaxies (<100 Mpc) like M82 and NGC 253
- Nearby Radio Galaxies (M87 and Cen a)
- Blazars (up to z~1-2)
- Clusters of Galaxies (within 100 Mpc - Coma, Perseus)
- GRBs? (the tails > 20 GeV)
- something unexpected
Topics

Theory of Particle Acceleration

Origin of Extragalactic Galactic Cosmic Rays (above $10^{18}$ eV)

Physics and Astrophysics of Supermassive Black Holes

Relativistic hydrodynamics of Relativistic Jets

Extragalactic Radiation Fields (First Stars, Galaxy Formation)

Structure of the IGM (Magnetic Fields, Large Scale Structure)

Tests of Fundamental Physics
Potential VHE Gamma Ray Sources

Major Scientific Topics

origin of GCRs
Relativistic Outflows
Compact Objects
EXG-CRs
Cosmology

Galactic

GeV ISM
GeV SFRs
GeV SNRs
GeV Pulsars
GeV Binaries

GMCs
Magnetosphere
Cold Wind
Pulsar Nebula
Microquasars
Binary Pulsars

Extragalactic

GeV GRBs
GeV AGN
GeV GLX
GeV CLUST
GeV IGM

EBL

Normal
Starburst

Radiogalaxies
Blazars

GRBs
AGN
GLX
CLUST
IGM
**Active Galactic Nuclei: AGN**

- Active Galaxies - galaxies with a compact, variable bright core (nucleus) the radiation of which is comparable or dominates over the emission of the host galaxy produced by stars (and partly reproduced by dust)

- AGN - central engines powered by Black Holes of $10^6$ to $10^{10} M_\odot$

- Radiation of AGN: thermal emission of the accretion flow and nonthermal emission of the relativistic jet

- several types of AGN - distinction between them sometimes arbitrary, but it is clear that we deal with several AGN populations - Seyfert galaxies, Quasars, Radio galaxies, BL Lac Objects,…

  **difference between these classes?**

- spectral lines e.g. Seyferts - rich line spectra, BL Lacs - featureless continuous
- large scale morphology e.g. radio galaxies - often with tween-lobed structures
- luminosity e.g. Seyferts - $10^{43}$-$10^{45}$ erg/s; QSO: $>10^{46}$ erg/s
- polarization, variability, etc.
Nonthermal features: Particle *Production Sites, Scenarios, Mechanisms*

jet – approximately 20 arcsec

1 arcsec = 3 kpc (z=0.158, Ho= 65 km/s Mpc

from R to X rays - nonthermal emission:
one should expect also gamma-rays on all
from sub-pc scales to multi-kpc scales!

high (GeV) and very high (TeV) energy g-rays have been
reported from hundreds and tens of AGN, respectively!

almost all of them are **blazars** – objects with relativistic jets
directed towards the observer


**sites**

- Jet
- Narrow Line Region
- Broad Line Region
- Black Hole
- Accretion Disk
- Obscuring Torus

**acceleration**

- (sub) relativistic shocks
- convertor mechanism
- stochastic (Fermi II)
- magnetic reconnection,
  …….

**radiation**

- Inverse Compton
- electron synchrotron
- Proton synchrotron
- photomeson processes
  (and subsequent cascades)
- $\gamma-\gamma$ pair production

- plus very complex \textit{magnetohydrodynamics}

- gamma-ray images of AGN – not possible, the only information through energy spectra and variability

\[ \Rightarrow \text{ broad range of possible realization (scenarios)} \]

BH magnetosphere

- sub-parsec jet
- pc-scale jet
- multi-pc jet
- multi-kpc lobes

\[ \textit{Urry and Padovani 1999} \]
SED of 3C 279 – a classical GeV blazar

$L_{\gamma}/L_S > 10$ | Synchrotron peak at mm & MIR | X-rays of IC origin | variability - days

TeV emission?
a typical TeV blazar: Mkn 421

a typical TeV blazar: Mkn 501
TeV blazar PKS 2155-304 in a low state

my opinion: *I cannot agree with such a statement: it is poorly justified and misleading if the low-state SED in reality is a superposition of weak flares – the parameters will be different; also usually the role of multiple “breaks” is overestimated, while the shape at cutoff is underestimated. What to do? Better nothing, rather than ‘one-zone model’ “industry”.

Aharonian et al. (HESS col.) 2009

one zone SSC model

electron spectrum:
power-law with two breaks:
\( p_1=1.3, p_2=3.2, p_3=4.3 \)
\( \gamma_1=1.4\times10^4, \gamma_2=2.3\times10^5 \)
and cutoff at \( \gamma_{\text{max}}=3\times10^6 \)
\( B=0.02 \text{ G}, R=2\times10^{17} \text{ cm}, \delta=32 \)

with a standard remark:
“SSC is a simplification but it satisfactorily explains the SED and gives correct parameters”
When we deal with AGN we should remember that generally the acceleration and radiation processes proceed under extreme physical conditions in environments characterized with huge gravitational, magnetic and electric fields (in the cores) very dense background radiation relativistic bulk motions (black-hole jets with $\delta > 10$) shock waves, highly excited (turbulent) media, etc.

in $\gamma$-ray emitting AGN everything should proceed with an extreme efficiency: conversion of the gravitational, thermal, bulk motion, electromagnetic forms of energy to nonthermal relativistic particles, i.e. effective acceleration of GeV/TeV/PeV/EeV particles coupled with favourable conditions for production of gamma-rays

SMBH and relativistic Doppler boosting – not sufficient: AGN - extremely effective particle accelerators and effective emitters
suspected sites of $10^{20}$ eV cosmic rays based on the condition: source size > Larmor radius

necessary but not sufficient condition: it implies

(1) minimum acceleration time

$$t_{\text{acc}} = \frac{R_L}{c} = \frac{E}{eBc}$$

acceleration in fact is slower:
$$t_{\text{acc}} = (1-10)\eta \frac{R_L}{c} \left(\frac{c}{v}\right)^2$$

with $\eta > 1$ and shock/bulk-motion speed $v < c$ ($\eta = 1$ - Bohm diffusion)

Compact objects like AGN and GRBs are the best candidates

(2) no energy losses

but synchrotron/curvature losses in compact objects become severe limiting factor

$$\frac{R}{1\text{pc}} \left(\frac{B}{1\text{G}}\right) > 0.1 \left(\frac{E}{10^{20}\text{eV}}\right)$$

“Hillas plot”

acceleration sites of $10^{20}$ eV CRs?

$$t_{\text{acc}} = \frac{R_L}{c} \eta^{-1}$$

signatures of extreme accelerators?

- \( \checkmark \) synchrotron self-regulated cutoff: 
  $$h\nu_{\text{cut}} = \frac{9}{4} \alpha_f^{-1} mc^2 \eta :$$

  \( \approx 300 \text{GeV} \) proton synchrotron
  \( \approx 150 \text{MeV} \) electron synchrotron

- \( \checkmark \) neutrinos (through “converter” mechanism) 
  production of neutrons (through \( p\gamma \) interactions) 
  which travel without losses and at large distances 
  convert again to protons \( \Rightarrow \Gamma^2 \) energy gain!

  Derishev, FA et al. 2003, Phys Rev D 68 043003

- \( \checkmark \) observable off-axis radiation 
  radiation pattern can be much broader than \( 1/\Gamma \)


*) in nonrelativistic shocks

\( \eta \approx 0.1 (v_{\text{shock}}/c)^2 \)
Blazars - sub-class of AGN dominated by nonthermal/variable broad band (from R to gamma) adiation produced in relativistic jets close to the line of sight, with massive Black Holes as central engines. Typically small B-field, $B < 1\, \text{G}$.

Gamma-rays from >100 Mpc sources - detectable because of Doppler boosting.
large Doppler factors: make more comfortable the interpretation of variability timescales (larger source size, and longer acceleration and radiation times), reduces (by orders of magnitude) the energy requirements, allow escape of GeV and TeV γ-rays ($\tau_{\gamma\gamma} \sim \delta_{j}^{6}$)

uniqueness: Only TeV radiation tells us unambiguously that particles are accelerated to high energies (one needs at least a TeV electron to produce a TeV photon) in the jets with Doppler factors $> 10$, otherwise gamma-rays cannot escape the source due to severe internal photon-photon pair production.

combined with synchrotron: derivation of several basic parameters like B-field, total energy budget in accelerated particles, thus to develop a quantitative theory of MHD, particle acceleration and radiation in relativistic jets, although yet with many conditions, assumptions, caveats...
Hadronic vs. Electronic models of TeV Blazars

SSC or external Compton – currently most favoured models:
- easy to accelerate electrons to TeV energies
- easy to produce synchrotron and IC gamma-rays
  recent results require more sophisticated leptonic models

Hadronic Models:
- protons interacting with ambient plasma
  very slow process:
- protons interacting with photon fields
  low efficiency + severe absorption of TeV $\gamma$-rays
- proton synchrotron
  very large magnetic field $B=100$ G + acceleration rate $c/r_g$

“extreme accelerator” (of EHE CRs) Poynting flux dominated flow

*detectable neutrinos from EGRET AGN but not from TeV blazars
Synchrotron radiation of an extreme proton accelerator

\[ E_{\text{cut}} = 90 \left( \frac{B}{100 \text{G}} \right) \left( \frac{E_p}{10^{19} \text{ eV}} \right)^2 \text{ GeV} \]

\[ t_{\text{synch}} = 4.5 \times 10^4 \left( \frac{B}{100 \text{G}} \right)^{-2} \left( \frac{E}{10^{19} \text{ eV}} \right)^{-1} \text{ s} \]

\[ t_{\text{acc}} = 1.1 \times 10^4 \left( \frac{E}{10^{19}} \right) \left( \frac{B}{100 \text{G}} \right)^{-1} \text{ s} \]

\[ E_{\text{max}} = 300 \eta^{-1} \delta j \text{ GeV} \]

requires extreme accelerators: \( \eta \sim 1 \)
Spectrometry beyond $3E_{\text{cutoff}}$!

Unprecedented photon statistics

Mkn 421 - 60,000 TeV photons detected in 2001
Mkn 501 - 40,000 TeV photons detected in 1997

spectra: canonical power-law with exponential cutoff

Cutoff = 6.2 TeV and 3.8 TeV for Mkn 501 and Mkn 421

time average spectra of Mkn 421 and Mkn 501
intergalactic absorption of gamma-rays
gamma-ray blazars and EBL
HESS – upper limits on EBL at O/NIR:

EBL (almost) resolved at NIR?

HESS upper limits
lower limits from galaxy counts
favored EBL – before HESS

$v(\nu)$ [nW/m² sr]

$\lambda[\mu m]$

$E_{\gamma}(TeV)$
new “trouble-makers”

1ES 0229+200: z = 0.14, but spectrum extends to >5 TeV! (HESS collaboration)

3C 66A z = 0.44! (VERTAS collaboration)
most exciting results of recent years

- ultra short time variability (on min scales)
- Jet powers could exceed Eddington luminosity
- extremely hard energy spectra
several min (200s) variability timescale $\Rightarrow R = c \Delta t_{\text{var}} \delta_j = 10^{14}\delta_{10}$ cm

for a $10^9$Mo BH with $3R_g = 10^{15}$ cm $\Rightarrow \delta_j > 100$, i.e. close to the accretion disk (the base of the jet), the bulk motion $\Gamma > 100$

rise time $<200$s
on the Doppler boosting and mass of BH in PKS2155-309

- several min variability timescale => \( R = c t_{\text{var}} \delta_j \sim 10^{13} \delta_j \) cm for a 10\(^9\)Mo BH with \( 3R_g \sim 10^{15} \) cm => \( \delta_j > 100 \), i.e. close to the accretion disk (the base of the jet), the Lorenz factor of the jet \( \Gamma > 50 \) - this hardly can be realized close to \( R_g \)!

- the (internal) shock scenario: shock would develop at \( R = R_g \Gamma^2 \), i.e. minimum \( \gamma \)-ray variability would be \( R_g/c = 10^4 (M/10^9 \text{Mo}) \) sec, although the \( \gamma \)-ray production region is located at \( R \sim c t_{\text{var}} \Gamma^2 \) (e.g. Chelotti, Fabian, Rees 1998) - this is true for any other scenario with a “signal-perturbation” originating from the central BH

- thus for the observed \( t_{\text{var}} < 200 \) s, the mass of BH cannot significantly exceed 10\(^7\)Mo. On the other hand the “BH mass–host galaxy bulge luminosity“ relation for PKS2155-304 gives \( M > 10^9 \text{Mo} \).

Solution? perturbations are cased by external sources, e.g. by magnetized condensations (“blobs”) that do not have direct links to the central BH; do we deal with the scenario “star crosses the relativistic \( e^+e^- \) jet}?
B-field: very large or very small?

in powerful blazars at subparsec scales B-field cannot be smaller than 1G, a serious constraint for the simplified one-zone “leptonic models,
M 87 – evidence for production of TeV gamma-rays close to BH?

- Distance: ~16 Mpc
- central BH: $3 \times 10^9 \, M_\odot$ *)
- Jet angle: ~30°
  => *not a blazar*!

Discovery ($>4\sigma$) of TeV $\gamma$-rays by HEGRA (1998) and confirmed recently by HESS/VERITAS, MAGIC

*) recently $6.4 \times 10^9 \, M_\odot$

M87: light curve and variability

HESS Collaboration 2006, Science, 314, 1427

short-term variability on 1-2 day scales ⇒ emission region $R \sim 5 \times 10^{15} \delta j$ cm
⇒ production of gamma-rays very close to the ‘event horizon’ of BH?

because of very low luminosity of the core in O/IR:
TeV gamma-rays can escape the production region

$L_{\text{IR}} \approx 10^{-8} L_{\text{Edd}}$
Simultaneous TeV and radio observations allow localization of gamma-ray production region within 50 $R_s$.

Monitoring of the M87 inner jet with VLBA at 43 GHz (ang. res. 0.21x0.43 mas) revealed increase of the radio flux by 30 to 50% correlated with the increase in TeV gamma-ray flux in Feb 2008.

**Conclusion?**

$TeV$ gamma-rays are produced in the jet collimation region within 50 $R_s$ around BH.
Pair Halos

TeV Gamma-rays from distant extragalactic sources, \( d > 100 \) Mpc interact effectively with Extragalactic Background Radiation (EBL; (0.1-100 mm))

- when a gamma-ray is absorbed its energy is not lost!
- absorption in EBL leads to E-M cascades supported by
  - Inverse Compton scattering on 2.7 K CMBR photons
  - photon-photon pair production on EBL photons

if the intergalactic field is sufficiently strong, \( B > 10^{-11} \) G,
the cascade \( e^+e^- \) pairs are promptly isotropised

formation of extended structures - Pair Halos
how it works?

- Energy of primary gamma-ray:
  \[ E_{\gamma,0} \approx 10 \left( \frac{E_{\gamma}}{100 \text{GeV}} \right)^{1/2} \text{ TeV} \]

- Mean free path of parent photons:
  \[ \lambda(E_{\gamma,0}) \approx d \times \Theta \]

Information about EBL flux at

\[ \lambda \approx 10 \left( \frac{E_{\gamma}}{100 \text{GeV}} \right)^{1/2} \mu \text{m} \]

Gamma-radiation of pair halos can be recognized by its distinct variation in spectrum and intensity with angle, and depends rather weakly (!) on the features of the central VHE source.

Two observables – angular and energy distributions allow to disentangle two variables \( u_{\text{EBL}}(\lambda, z) \) and \( d (H_0) \).
Pair Halos as Cosmological Candles

- information about EBL density at fixed cosmological epochs given by the redshift of the central source
- estimate of the total energy release of AGN during the active phase
- objects with jets at large angles - many more γ-ray emitting AGN
  but the advantage of the large Doppler boosting of blazars disappears: beam => isotropic source
  therefore very powerful central objects needed

QSOs and Radiogalaxies (sources of EHE CRS ?) as better candidates for Pair Halos
this requires low-energy threshold detectors
EBL at different $z$ and corresponding mean freepaths

![Graphs showing EBL at different $z$ and corresponding mean freepaths.](image)
SEDs for different $z$ within $0.1^\circ$ and $1^\circ$

EBL model – Primack et al. 2000

$L_0=10^{45}$ erg/s
Brightness distributions of Pair Halos

$E_\gamma > 10 \text{ GeV}$  $E_\gamma > 100 \text{ GeV}$  $E_\gamma > 500 \text{ GeV}$  $E_\gamma > 1 \text{ TeV}$

$z = 0.034$  $z = 0.129$  $z = 1.0$  $z = 2.0$

$z = 0.129$  $E = 10 \text{ GeV}$