GLAST – NuSTAR synergies in unraveling the structure of jets in active galaxies

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Outline:

• Jet-dominated AGN as gamma-ray sources
• Emission processes and content the relativistic jet
• Future observational prospects in the high energy regime towards the answers: GLAST and NuSTAR
Radio, optical and X-ray images of the jet in M 87

Jets are common in AGN – and radiate in radio, optical and X-ray wavelengths
Astrophysical jets and blazars: what are blazars?

• Blazars are active galaxies with prominent relativistic jets
• Jets are clearly visible in high-resolution radio images
• Blazars are commonly detected as MeV – GeV and even TeV $\gamma$-ray emitters (~ 60 detected by EGRET)
• Rapidly variable in all bands including $\gamma$-rays
• Variability of $\gamma$-rays implies compact source size, where the opacity of GeV $\gamma$-rays against keV X-rays to $e^+/e^-$ pair production would be large – sources would be opaque to their own emission!
• Entire electromagnetic emission ($\gamma$–rays too!) most likely arises in a relativistic jet with Lorentz factor $\Gamma_j \sim 10$, pointing close to our line of sight
• The observed emission is WAY brighter than would be for a non-relativistic jet (Doppler boosting: $\text{Flux}_{\text{obs}} \sim \text{Flux}_{\text{iso}} \times \Gamma_j^4$)
Unified picture of active galaxies

- Presumably all AGN have the same basic ingredients: a black hole accreting via disk-like structure

- In blazars the jet is most likely relativistically boosted towards us and thus so bright that its emission masks the isotropically emitting “central engine”
EGRET All-Sky Map (>100 MeV)

Cygnus Region

3C279

Vela

Geminga

Crab

PSR B1706-44

PKS 0208-512

LMC

PKS 0528+134

Cosmic Ray Interactions With ISM
Blazars are variable in all observable bands

Example: X-ray and GeV $\gamma$-ray light curves from the 1996 campaign to observe 3C279

Plot showing the lightcurves of 3C 279 from EGRET (top) and XTE (bottom) during the flare in early 1996

$\gamma$-rays

X-rays
Broad-band spectra of blazars

Example of a spectrum of an EGRET blazar: 3C279
(data from Wehrle et al. 1998)

Example of a spectrum of a TeV blazar: Mkn 421
(data from Macomb et al. 1995)
Radiative processes in blazars

• What do we infer? We have some ideas about the radiative processes…

  – Polarization and the non-thermal spectral shape of the low energy component are best explained via the synchrotron process: relativistic electrons experience Lorentz force in magnetic field, are accelerated, radiate

  – The high-energy component is most likely due to the inverse Compton process by the same relativistic particles that produce the synchrotron emission, Compton-upscatter internal or external radiation

  – Relative intensity of the synchrotron vs. Compton processes depends on the relative energy density of the magnetic field vs. the ambient “soft” photon field

• BUT – WE STILL DON'T KNOW HOW THE JETS ARE LAUNCHED, ACCELERATED AND COLLIMATED – AND WHAT IS THEIR CONTENT

• TO MAKE SOME PROGRESS ON THIS FRONT, WE SHOULD AT LEAST KNOW THE COMPOSITION OF THE JET
  (electrons-protons? electron-positrons?)
Modelling of radiative processes in blazars

• In the context of the synchrotron models, emitted photon frequency is 
  \[ \nu_s = 1.3 \times 10^6 B \times \gamma_{el}^2 \text{ Hz} \]
  where \( B \) is the magnetic field in Gauss
  and \( \gamma_{el} \) is the electron Lorentz factor

• The best models have \( B \sim 1 \) Gauss, and \( \gamma_{el} \) for electrons radiating at the
  peak of the synchrotron spectral component of \( \sim 10^3 \text{ – } 10^6 \),
  depending on the particular source

• Degeneracy between \( B \) and \( \gamma_{el} \) is “broken” by spectral variability
  + spectral curvature (Perlman et al. 2005)

• The high energy (Compton) component is produced by the same
  electrons as the synchrotron peak and \( \nu_{\text{compton}} = \nu_{\text{seed}} \times \gamma_{el}^2 \text{ Hz} \)

• Still, the jet Lorentz factor \( \Gamma_j \) is \( \sim 10 \), while Lorentz factors of
  radiating electrons are \( \gamma_{el} \sim 10^3 \text{ – } 10^6 \)

• Must find a mechanism to convert the “bulk flow” of the jet \((\Gamma_j \sim 10)\)
  to “random motion” of electrons \((\gamma_{el} \sim \text{ thousands})\)
Photon and electron spectra

- Radiation energy spectra often have power-law shape, \( P(E) = P_0 E^{-\alpha} \)
- It is easy to show that for synchrotron or inverse Compton radiation, such a spectral form arises from a power-law distribution of the number of radiating electrons, \( N(\gamma) = N_0 \gamma^{-p} \) where \( \alpha = (p-1)/2 \)
- This means that for most typical spectra, the least-energetic particles are most numerous – they are the bulk of the jet!
Even in this extreme case of a very hard X-ray spectrum of a blazar, the lowest energy particles dominate by number.

(data from Blazejowski et al. 2004)

- Low-energy (synchrotron) component cannot be used to study the lowest end of the electron energy distribution (via “easy” radio observations) – the compact regions are opaque to self-absorption
- The only hope to study the low-energy, most numerous particles is the hard X-ray / soft $\gamma$-ray regime -> NuSTAR
- Simultaneous observations will be needed as the sources are variable
Viable mechanism for particle acceleration - colliding shells model:
Shells move with Lorentz factors $\Gamma$ where $\Gamma_2 > \Gamma_1$, shell 2 collides with shell 1, a shock forms, and particles are accelerated via Fermi process in shocks.
Content of the jet

- Are blazar jets dominated by kinetic energy of particles from the start, or are they initially dominated by magnetic field (Poynting flux)? (Blandford; Vlahakis; Wiita; Meier; Hardee; ...)

- There is a critical test of this hypothesis, at least for quasar-type ("EGRET") blazars:

  - *If the kinetic energy is carried by particles*, the radiation environment of the AGN should be bulk-Compton-upscattered to X-ray energies by the cold electrons associated with the bulk motion of the jet

  - If $\Gamma_{\text{jet}} = 10$, the $\sim 10$ eV H Ly$\alpha$ photons should appear bulk-upscattered to $10^2 \times 10$ eV $\sim E > 1$ keV (E is higher for "hotter" internal electrons)

  - X-ray flare should precede the $\gamma$-ray flare (form a "precursor")

  - X-ray monitoring concurrent with GLAST observations is crucial to settle this

  - A lack of X-ray precursors would imply that the jet is "particle-poor" and may be dominated (at least initially) by Poynting flux
From Sikora, Begelman, and Rees 1994

- Source of the “seed” photons for inverse Compton scattering can depend on the environment

- It can be the synchrotron photons internal to the jet (the “synchrotron self-Compton” model)

  - This is probably applicable to BL Lac objects such as Mkn 421

- Alternatively, the photons can be external to the jet (“External Radiation Compton” model)

  - This is probably applicable to blazars hosted in quasars such as 3C279
GLAST LAT’s ability to measure the flux and spectrum of 3C279 for a flare similar to that seen in 1996 (from Seth Digel)