Relativistic jets and the Radio/γ-ray connection

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Outline

- Background
- The tip of the iceberg: bright and flaring blazars
- Uncommon γ-ray emitters: what's new
- Conclusions
3FGL catalog

4 years of Fermi-LAT observations

3033 sources:
- 2041 associated with a low-energy counterpart
- 992 not associated

Acero+15
The extragalactic γ-ray sky

1752 (58%) extragalactic objects
1718 (98%) blazar-like sources
15 radio galaxies
5 NLSy1
7 normal galaxies (γ-ray from cosmic rays)

Savolainen+ 2010, Lister+ 09, Kovalev+ 2009

Strong γ-ray emitters:

• High radio luminosity
• Fast apparent jet speed
• High variability Doppler

Extragalactic γ-ray sky dominated by radio-loud AGN

Ackermann+15
The extragalactic γ-ray sky

Presence of relativistic jets

Only in 10% of AGN

Credit: H.-J. Röser

Credit: C. Carilli

3C 273 and its Jet

Credit: H.-J. Röser

Credit: C. Carilli
Relativistic jets

Non-thermal emission

• Low energy: **synchrotron**
  
  Relativistic electrons can scatter low energy photons

• High energy: **inverse Compton**

  **Seed photons:**

  • external photons from torus, disk, BLR... (External Compton)

  • their own synchrotron photons (Synchrotron-self Compton)

Blazar sequence

Luminosity $\sim 10^{49} - 10^{50}$ erg/s

Donato et al. 2001
**Relativistic jets**

**Non-thermal emission**

- Low energy: *synchrotron*

  Relativistic electrons can scatter low energy photons

- High energy: *inverse Compton*

  **Seed photons:**
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Ghirlanda et al. 2010

Existence of radio-gamma correlation for both BL Lacs and FSRQ
Relativistic jets

Non-thermal emission

- Low energy: synchrotron

  Relativistic electrons can scatter low energy photons

- High energy: inverse Compton

  Seed photons:
  - external photons from torus, disk, BLR... (External Compton)
  - their own synchrotron photons (Synchrotron-self Compton)

Existence of radio-gamma correlation for both BL Lacs and FSRQ
Open questions

• What is the γ-ray emitting mechanism?
• Where is the region responsible for γ-ray emission?
• Shock propagation, turbulence, velocity gradient?
• What is the structure of the magnetic field in the jet?
• .....
Open questions

Shock-in-jet model: where? how?

• Within the BLR:
  - IC with UV
  - γ-ray leads radio
  - No VHE emission

• ≈ 1 pc:
  - IC with IR
  - γ-ray and mm simultaneous

• > few parsecs:
  - SSC, IC with sync photons from a different e- population
  - γ-ray and mm simultaneous or radio leads γ-ray

Radio/γ-ray time lag depends on the location of the shock
**Single-dish studies of large samples: F-GAMMA**

Cross-correlation between the γ-ray and radio light curves of a sample of 54 Fermi blazars observed between 11 cm and 2 mm. Additional 0.8 mm APEX data for 25 blazars. 

**γ-ray leads the radio variability**

Time delay increases with frequency:

- 76±23 days at 11 cm
- 7±9 days at 2 mm

The γ-ray/radio distance decreases with frequencies:

- 9.8±3.0 pc at 11 cm
- 0.9±1.1 pc at 2 mm

Fuhrmann+14
**Single-dish studies of large samples: Metsähovi**

Cross-correlation between the radio and γ-ray light curves of a sample of 60 Fermi blazars observed at 37 GHz.

Radio leads the γ-ray variability in FSRQ

Time delay between the onset of the mm flare and the peak of the γ-ray flare

- 70 days - observer frame
- 30 days - source frame

The γ-ray region should be located ~ 7.4±1.3 pc downstream along the jet:

No clear radio/γ-ray correlation in BL Lacs
**How can we answer (or try to..)?**

High-resolution + multifrequency + multiepoch + polarimetry

Multi-epoch VLBI observations of flaring sources

- Cutini+14
- D'Ammando+13
- Orienti+14
- Kovalev+07
- FSRQ
- NLSy1
- High-z FSRQ
- RG
- Hada+13
The brightest blazar: 3C 454.3

The most active blazar in gamma rays during the first 3 years of Fermi.

An ideal candidate for studying the radio/γ-ray connection
Radio and γ-ray light curves

Orienti, in prep

The rise of the mm flux density precedes the γ-ray flare

→

γ-ray produced pc away from the core

→

γ-ray region opaque to cm emission
The $\gamma$-ray region

The increase of $\gamma$-ray and mm emission seems simultaneous. At 15 GHz it is delayed by about 2 months.

Co-spatiality of $\gamma$-ray and mm emission produced on pc scale

- IR photons from the dusty torus
- Synchro photons from different $e^-$ population

Reconfinement shock in toroidal magnetic field + IR photons
Superluminal knot is the observable manifestation of a propagating shock

Usually ejected close to a γ-ray flare

Some γ-ray flares without knot ejection
**Magnetic field**

- Single dish: EVPA rotates of about 90°

- VLBI: Flux and polarization dominated by the knot ejected in Dec 2009 interacting with a stationary shock

**Knot EVPA parallel to the jet axis**, as expected for internal shock or reconfinement shock in a **toroidal magnetic field** (e.g. Sikora+08)
**Observational clues**

WHERE?
- pc scale
- > 10 parsec

WHO?
- Internal shock
- Reconfinement shock
- Standing conical shock

HOW?
- IR from torus
- SSC
- Synchro from different e⁻ population

**Diagram**
- IR
- UV
- BLR
- Synchro/SSC
- TORUS
The γ-ray region

Pc-scale distance \( < 10^{16} \text{ cm} \)

Causality argument

Large changes in the inner jet position angle

Jet knot occupies only a fraction of the jet cross-section

Lister+13
A very active blazar: PKS 1510-089

Many bright $\gamma$-ray flares. Superluminal knots ejected $\sim$ every year

A FSRQ Detected above 100 GeV!
**Shock stages**

Multifrequency: schock stages + VLBI: Detection of superluminal knots

Orienti+13 PKS 1510-089

Peak flux density depends on the shock stage.

The γ-ray and mm flare seems **simultaneous**. Delayed at longer λ

Cospatiality in a pc-scale region

Not all γ-ray flare close in time with the ejection of superluminal knots
Polarization: core component

Optical flare close to the γ-ray flare

Optical EVPA rotates ~380° in 7 days

Shock within the BLR moving in a helical magnetic field

The interaction with a standing shock at pc-scale distance may produce the second huge flare
As the knot emerges from the core its EVPA aligned to ~ 80°

Polarization: jet component

Orienti+, in prep

EVPA of the knots is roughly \( \perp \) to the jet axis.

Oblique shock?

Reconfinement shock in a chaotic B?
**Observational clues**

WHERE?  
- < pc  
- pc scale  
- > 10 parsec

WHO?  
- Magnetic field reconnection
- Internal shock
- Reconfinement shock
- Standing conical shock
- Synchro from different e\(^{-}\) population

HOW?  
- UV/optical from BLR
- IR from torus
- SSC
- Synchro from different e\(^{-}\) population

Different flares from different regions along the same jet
SBS0846+513: relativistic jet in NLSy1

No $\gamma$-ray flare detected close in time with the ejection of a new jet component.

*No seed photons?*

No clear radio/$\gamma$-ray connection
The radio galaxy NGC 1275

3C 84 is a nearby $z=0.0176$ radio galaxy with recurrent radio activities.

A: $\sim 10$ kpc, $t_{\text{syn}} \sim 10^5$ yr

B: $\sim 10$ pc, $\sim 50$ yr, 1959?

C: $\sim 1$ pc, $\sim 5$ yr, 2005?

Detected by Fermi with luminosity 7 times higher than EGRET limit

-$\gamma$-ray variability, origin $< 1$ pc?

Pedlar+90

Nagai+10

Abdo+09
**The trigger: two zone model – 3C 84**

- Detected at VHE by MAGIC
- No radio/γ-ray correlation
- No superluminal component
- Limb-brightened when γ-ray-loud
- Edge-darkened when γ-ray-quiet

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SED NOT consistent with one-zone region, e.g. shock

- SED consistent with a spine-layer model

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Dhawan et al. 1996

Tavecchio & Ghisellini 2014
Open questions

WHERE?

- Sub-pc scale
- pc scale
- > 10 parsec
- Two-zone model

WHO?

- Magnetic field reconnection
- Internal shock
- Reconfinement shock
- Standing conical shock
- Velocity gradient
- Synchro from different e⁻ population

HOW?

- UV, optical from BLR
- IR from torus
- Synchro from different e⁻ population

Ghisellini+08
Not only jets

What about high-z $\gamma$-ray blazars?

Only a few high-z blazars (64 in the 3FGL)

Faint and soft sources

They become very luminous and harder during flares

Extragalactic Background Light studies!
High-z blazar TXS 0536+145 (z=2.69)

Radio delayed by 4-5 months (obs frame)

Orienti+14

It is the γ-ray flaring blazar at the highest redshift detected so far
High-z γ-ray blazars and the EBL

$L_\gamma - z$

$\Gamma - L_\gamma$
**TXS 0536+145 and the EBL**

Spectral hardening:

Average  \( \Gamma = 2.37 \pm 0.09 \)

Flare  \( \Gamma = 2.05 \pm 0.08 \)

At \( z = 2.69 \), the optical depth \( \tau \sim 1 \) should be at 40 Gev (Finke 2010)

The highest photon energy is 11.2 GeV, compatible with the EBL models.
Summary

γ-ray sky dominated by blazar population

Connection between radio and γ-ray emission

Flaring γ-ray emission from different region of the jet

The trigger: shock-in-jet or velocity gradient

Change in the jet structure

High-z blazars and the EBL