Prospects for High-Energy and Multi-Wavelength Polarimetry of Blazars

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Quasar 3C175
YLA 6cm image (c) NRAO 1996

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Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars with relativistic jets pointing close to our line of sight
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio knots often with superluminal motion
- Radio and optical polarization
Blazar Spectral Energy Distributions (SEDs)

Non-thermal spectra with two broad bumps:
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- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
Blazar Spectral Energy Distributions (SEDs)

Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(-UV-X-rays)
- High-energy (X-ray – $\gamma$-rays)

3C66A

3C279

MAGIC
Blazar Classification

Low-Synchrotron Peaked (LSP): Quasars (FSRQs)/Low-frequency peaked BL Lac Objects (LBLs)

Low-frequency component from radio to optical/UV,

\[ \nu_{sy} \leq 10^{14} \text{ Hz} \]

High-frequency component from X-rays to \( \gamma \)-rays, often dominating total power

(Hartman et al. 2000)
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High-Synchrotron Peaked (HSP): High-frequency peaked BL Lacs (HBLs):

Low-frequency component from radio to UV/X-rays,
\[ \nu_{sy} > 10^{15} \text{ Hz} \]

often dominating the total power

High-frequency component from hard X-rays to high-energy gamma-rays

(Hartman et al. 2000)

(Acciari et al. 2009)
**Blazar Classification**

**Low-Synchrotron Peaked (LSP):** Quasars (FSRQs) / Low-frequency peaked BL Lac Objects (LBLs)

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- High-frequency component from X-rays to $\gamma$-rays, often dominating total power

**Intermediate-Synchrotron Peaked (ISP):** Intermediate BL Lacs (IBLs):

- Peak frequencies at IR/Optical and GeV gamma-rays,
  \[ 10^{14} \text{ Hz} < \nu_{sy} \leq 10^{15} \text{ Hz} \]
- Intermediate overall luminosity
- Sometimes $\gamma$-ray dominated

**High-Synchrotron Peaked (HSP):** High-frequency peaked BL Lacs (HBLs):

- Low-frequency component from radio to UV/X-rays,
  \[ \nu_{sy} > 10^{15} \text{ Hz} \]
- Often dominating the total power
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(Hartman et al. 2000)

(Abdo et al. 2011)

(Acciari et al. 2009)
Flux and Polarization Variability

Multi-wavelength variability on various time scales (months – minutes)
Sometimes correlated, sometimes not

(3C279: Abdo et al. 2010)
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Observed optical polarization degrees $\Pi_{\text{opt}} \lesssim 30\%$
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Multi-wavelength variability on various time scales (months – minutes)
Sometimes correlated, sometimes not

Observed optical polarization degrees \( \Pi_{\text{opt}} \sim 30\% \)

Both degree of polarization and polarization angles vary.
Swings in polarization angle sometimes associated with high-energy flares!
Open Physics Questions

- Source of Jet Power (Blandford-Znajek / Blandford-Payne?)

- Physics of jet launching / collimation / acceleration – role / topology of magnetic fields

- Composition of jets (e⁻-p or e⁺-e⁻ plasma?) – leptonic or hadronic high-energy emission?

- Mode of particle acceleration (shocks / shear layers / magnetic reconnection?) - role of magnetic fields

- Location of the energy dissipation / gamma-ray emission region
Leptonic Blazar Model

Relativistic jet outflow with $\Gamma \approx 10$
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Injection, acceleration of ultrarelativistic electrons

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Relativistic jet outflow with $\Gamma \approx 10$

Radiative cooling $\leftrightarrow$ escape $\Rightarrow$

$$Q_e(\gamma,t) = \gamma^{-q}$$

$$\tau_{cool}(\gamma_b) = \tau_{esc}$$
Leptonic Blazar Model

Injection, acceleration of ultrarelativistic electrons

Relativistic jet outflow with $\Gamma \approx 10$

Synchrotron emission

Radiative cooling $\leftrightarrow$ escape $\Rightarrow$

$Q_e(\gamma,t) = \gamma^{-q}$ or $\gamma^{-(q+1)}$

$\gamma_b$, $\gamma_1$, $\gamma_2$

$\gamma_b$:
$\tau_{\text{cool}}(\gamma_b) = \tau_{\text{esc}}$

$\nu F_{\nu}$
Leptonic Blazar Model

Injection, acceleration of ultrarelativistic electrons

Relativistic jet outflow with $\Gamma \approx 10$

Radiative cooling $\leftrightarrow$ escape $\Rightarrow$

$Q_{\gamma}(\gamma, t)$

$\gamma^{-q}$ or $\gamma^{-2}$

Seed photons:
- Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

$\gamma_{b}$:
$\tau_{\text{cool}}(\gamma_{b}) = \tau_{\text{esc}}$
Hadronic Blazar Models

Relativistic jet outflow with $\Gamma \approx 10$
Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

Relativistic jet outflow with $\Gamma \approx 10$

$Q_{e,p}(\gamma, t)$

$\gamma^{-q}$

$\gamma_1$, $\gamma_2$

Narrow Line Region

Broad Line Region

Jet

Black Hole

Accretion Disk

Obscuring Torus
Hadronic Blazar Models

- Injections, acceleration of ultrarelativistic electrons and protons
- Relativistic jet outflow with $\Gamma \approx 10$
- Synchrotron emission of primary $e^-$
- $Q_{e,p}(\gamma,t)\gamma^{-q}$

$\nu F_\nu$
Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

Relativistic jet outflow with $\Gamma \approx 10$

Synchrotron emission of primary $e^-$

Proton-induced radiation mechanisms:

$Q_{e,p}(\gamma,t)$

$\gamma^{-q}$

$\nu F_\nu$

$\nu F_\gamma$
Hadronic Blazar Models

Injection, acceleration of ultrarelativistic electrons and protons

Relativistic jet outflow with $\Gamma \approx 10$

Proton-induced radiation mechanisms:

- Proton synchrotron
  - $p\gamma \rightarrow p\pi^0$
  - $\pi^0 \rightarrow 2\gamma$

- $p\gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$

- $\mu^+ \rightarrow e^+\nu_e\nu_\mu$

- secondary $\mu^-$, e-synchrotron

- Cascades …

Synchrotron emission of primary e−

$Q_{e,p}(\gamma,t)$
Lepto-Hadronic Model Fits to Blazar SEDs

RGB J0710+591 (HBL)

Red = leptonic
Green = lepto-hadronic
In many cases, leptonic and hadronic models can produce equally good fits to the SEDs.
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Possible Diagnostics to distinguish:

- Neutrinos
- Variability
- Polarization
Possible Distinguishing Diagnostic: Polarization

- Synchrotron Polarization

For synchrotron radiation from a power-law distribution of electrons with $n_e (\gamma) \sim \gamma^{-p} \rightarrow F_{\nu} \sim \nu^{-\alpha}$ with $\alpha = (p-1)/2$

$$\Pi^{sy}_{PL} = \frac{p + 1}{p + 7/3} = \frac{\alpha + 1}{\alpha + 5/3}$$
Possible Distinguishing Diagnostic: Polarization

• Synchrotron Polarization

For synchrotron radiation from a power-law distribution of electrons with \( n_e(\gamma) \sim \gamma^{-p} \rightarrow F_\nu \sim \nu^{-\alpha} \) with \( \alpha = (p-1)/2 \)

\[
\Pi_{PL}^{sy} = \frac{p + 1}{\alpha + 1} = \frac{p + 7/3}{\alpha + 5/3}
\]

\( p = 2 \rightarrow \Pi = 69 \% \)

\( p = 3 \rightarrow \Pi = 75 \% \)
Compton Polarization

Compton cross section is polarization-dependent:

\[ \frac{d\sigma}{d\Omega} = \frac{r_0^2}{4} \left( \frac{\epsilon'}{\epsilon} \right)^2 \left( \frac{\epsilon}{\epsilon'} + \frac{\epsilon'}{\epsilon} - 2 + 4 \left[ \overrightarrow{e} \cdot \overrightarrow{e}' \right]^2 \right) \]

\[ \epsilon = \frac{h\nu}{m_e c^2} : \]

Thomson regime: \( \epsilon \approx \epsilon' \)

\[ \Rightarrow \frac{d\sigma}{d\Omega} = 0 \text{ if } \overrightarrow{e} \cdot \overrightarrow{e}' = 0 \]
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Thomson regime: \( \epsilon \approx \epsilon' \)

\( \Rightarrow \frac{d\sigma}{d\Omega} = 0 \) if \( e \cdot e' = 0 \)

\( \Rightarrow \) Scattering preferentially in the plane perpendicular to \( e \)!

Preferred polarization direction is preserved.
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\[\epsilon = h\nu/(m_e c^2):\]

Thomson regime: \[\epsilon \approx \epsilon'\]
\[\Rightarrow d\sigma/d\Omega = 0 \text{ if } \vec{e} \cdot \vec{e}' = 0\]

\[\Rightarrow \text{Scattering preferentially in the plane perpendicular to } \vec{e}!\]

Preferred polarization direction is preserved.
Compton Polarization

Compton scattering of an anisotropic radiation field by non-relativistic electrons induces polarization perpendicular to the plane of scattering.
Compton Scattering by Relativistic Electrons

- Relativistic aberration => approx. axisymmetric radiation field in co-moving frame of e-

- Unpolarized target photons (EC emission) → Unpolarized

- Polarized target photons (SSC) → SSC polarization ~ ½ of target (synchrotron) photon polarization
Multiwavelength Polarization of Blazars

![Diagram of a blazar with labels for accretion disk, dust torus, and various regions like Narrow Line Region, Broad Line Region, Jet, Accretion Disk, and Obscuring Torus. The diagram also includes a graph showing the PD (%) vs. frequency (ν [Hz]) and the νF,ν [Jy Hz] spectrum with bands for IXPE and AMEGO.]
Multiwavelength Polarization of Blazars

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

Graph showing:
- PD [%]
- $F_{\nu}$ [Jy Hz]
- $\nu$ [Hz]

Key:
- accretion disk
- dust torus
- e$^{-}$ synchrotron
- SSC
- EC
- leptonic total

Comparing with IXPE and AMEGO data.
Multiwavelength Polarization of Blazars

- Narrow Line Region
- Broad Line Region
- Jet
- Black Hole
- Accretion Disk
- Obscuring Torus
- Synchrotron
- SSC
- EC
- Leptonic Total
- Hadronic Total
- Dust Torus
- $\nu$ [Hz]
- $F_\nu$ [Jy Hz]
- PD [%]
- IXPE
- AMEGO

accretion disk
- dust torus
- $e^-$ synchrotron
- SSC
- EC
- leptonic total
- $p$ synchrotron
- $p\gamma$ cascades
- hadronic total
MWL Polarization of LSP blazars

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(SED from Bottacini et al. 2016)
MWL Polarization of LSP blazars

3C279

Optical Spectropolarimetry

Polarization Degree $\Pi$

Leptonic Model
Lepto-Hadronic Model
Synchrotron Component
EC BLR
EC Disk
SSC component
Electron Synchrotron
Proton Synchrotron
SMARTS
Swift-UVOT
Swift-XRT
INTEGRAL-IBIS/ISGRI
Fermi-LAT (Paliya 2015)

SED from Bottacini et al. 2016
Multiwavelength Polarization

Polarization Degree

$\Pi$

Disk

Sy

SSC

EC

Total

Optical Spectropolarimetry

$\lambda$

$\nu \cdot F_\nu$ [erg]

$10^{-12}$

$10^{-11}$

$10^{-10}$

$10^{-9}$

$10^{-8}$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^0$

$10^1$

$10^2$

$10^3$

$10^4$

$10^5$

$10^6$

$10^7$

$10^8$

$10^9$

$10^{10}$

$10^{11}$

$10^{12}$

$10^{13}$

$10^{14}$

$10^{15}$

$10^{16}$

$10^{17}$

$10^{18}$

$10^{19}$

$10^{20}$

$10^{21}$

$10^{22}$

$10^{23}$

$10^{24}$

$10^{25}$

Frequency [Hz]

Linear Polarization [%]

0

5

10

15

20

25

30

35

40

Wavelength $\lambda$

Sy

SSC

EC

Total

(Bottacini et al. 2016)
Multiwavelength Polarization

Polarization Degree $\Pi$

Disk

Sy

SSC

EC

Total

Optical Spectropolarimetry

Wavelength $\lambda$

Linear Polarization (%)

Frequency [Hz]

$\nu \nu F_{\nu}$ [erg]

Bottacini et al. 2016
The Southern African Large Telescope (SALT)
Example: 4C +01.02 (FSRQ at $z = 2.1$)

Large $\gamma$-ray (Fermi-LAT) flare in July 2016

(Schutte et al., in prep.)
Example: 4C +01.02 (FSRQ at z = 2.1)

SALT spectropolarimetry observations in July 2016 (flare) and July 2017 (quiescent)

Large $\gamma$-ray (Fermi-LAT) flare in July 2016

(Schutte et al., in prep.)
4C +01.02 (PKS B0106+013)

Significant (and time-variable) optical polarization, decreasing towards shorter wavelength => Addition of unpolarized component (accretion disk).
4C +01.02: Combined SED + spectropolarimetry modeling

(Schutte et al., in prep.)
4C +01.02: Combined SED + spectropolarimetry modeling

Tightly constrains BH mass ($4 \times 10^8 M_\odot$) and ordering of magnetic field:
- flare: $F_B = 0.15$
- quiescence: $F_B = 0.02$
X-Ray and Gamma-Ray Polarization: LSP Blazars

Hadronic model:
Synchrotron dominated
=> High $\Pi$, generally increasing with energy (SSC contrib. in X-rays).

Leptonic model:
X-rays SSC dominated:
$\Pi \sim 20 - 40 \%$;
$\gamma$-rays EC dominated
=> Negligible $\Pi$.

(Zhang & Böttcher, 2013)
X-Ray and Gamma-Ray Polarization: ISP Blazars

Hadronic model:
Synchrotron dominated => High $\Pi$, throughout X-rays and $\gamma$-rays

Leptonic model:
X-rays sy. Dominated => High $\Pi$, rapidly decreasing with energy; $\gamma$-rays SSC/EC dominated => Small $\Pi$.

(Zhang & Böttcher, 2013)
Observational Strategy

- Results shown here are **upper limits** (perfectly ordered magnetic field perpendicular to line of sight).

- Scale results to actual B-field configuration from known synchrotron polarization (e.g., optical for FSRQs/LBLs) =>
  Expect 10 - 20% X-ray and γ-ray polarization in hadronic models!

- X-ray and γ-ray polarization values substantially below synchrotron polarization will favor leptonic models, measurable γ-ray polarization clearly favors hadronic models!

(Zhang & Böttcher, 2013)
The “Big Blue Bump”

- Accretion disk + Corona? → **Unpolarized**
- Additional synchrotron component? → **Moderately polarized**
- Bulk Compton scattering of external radiation field by thermal electrons → **Potentially highly polarized**

Baring et al. (2017):
Monte-Carlo simulations of Diffusive Shock Acceleration

→ Modeling of the soft X-ray excess as bulk Comptonization of IR radiation from dusty torus by shock-heated, thermal electrons tightly constrains thermal vs. non-thermal particle populations

→ Tight constraints on pitch-angle diffusion and plasma parameters
Simulating Polarization of the Bulk Compton Feature

- If due to bulk Compton, the soft X-ray excess in AO 0235+164 could be polarized up to ~ 50 % in soft X-rays (if viewing angle ~ $1/\Gamma$).

X-Ray and Gamma-Ray Polarization: HBLs

In both leptonic and hadronic models, optical and X-ray emission are dominated by jet synchrotron.

X-ray polarimetry may reveal mode of particle acceleration:

- Magnetic reconnection: Acceleration in turbulent regions → Low PD
- Shocks: Significant (up to 50 %) X-ray polarization; likely higher PD in X-rays than in the optical (smaller emission region?)

(Tavecchio et al. 2018)
X-Ray and Gamma-Ray Polarization: HBLs

Evidence for particle acceleration + B-field compression at shocks across blazar classes

(Angelakis et al. 2016 – ROBOPOL)
**Caution: PA Swings**

- Sometimes Optical / γ–ray flares are correlated with increase in optical polarization and multiple rotations of the polarization angle (PA)
- Duration typically several days
- X-ray polarimetry observations of faint sources may require day-long observations → Polarization measurement smeared out / destroyed!
- Models proposed for PA swings:
  - Helical jet/pattern motion
  - Turbulent cells → Stochastic PA variations (TEMZ)
  - Kink instabilities
  - Helical B-fields in internal shocks (see Böttcher 2019 for a review and refs.)

PKS 1510-089 (Marscher et al. 2010)
Tracing Synchrotron Polarization in the Internal Shock Model

Viewing direction in obs. Frame: $\theta_{\text{obs}} \sim 1/\Gamma$

Viewing direction in comoving frame: $\theta_{\text{obs}} \sim \pi/2$

3DPol (Zhang et al. 2014)

- Solve electron dynamics and radiation transfer with Monte-Carlo / Fokker-Planck scheme (Chen et al. 2011, 2012)

- Time-dependent, polarization-dependent ray tracing for polarization signatures
Light Travel Time Effects

Shock positions at equal photon-arrival times at the observer

(Zhang et al. 2015)
Simultaneous optical + \( \gamma \)-ray flare, correlated with a 180\(^\circ\) polarization-angle rotation.

(AbdO et al. 2010)
Simultaneous optical + $\gamma$-ray flare, correlated with a 180° polarization-angle rotation.

(Abdo et al. 2010)
Application to 3C279

Simultaneous fit to SEDs, light curves, polarization-degree and polarization-angle swing

(Zhang et al. 2015)
Application to 3C279

Requires particle acceleration and reduction of magnetic field, as expected in magnetic reconnection!

(Zhang et al. 2015)
The Lepto-Hadronic Version

- Lepto-hadronic (p-synchrotron dominated) 3D time- and polarization-dependent internal shock model (Zhang, Diltz & Böttcher 2016)
- Model setup as for leptonic (3DPol) model, but include injection of ultrarelativistic protons
- Electron + proton evolution with locally isotropic Fokker-Planck equation
- Fully time- and polarization-dependent ray tracing
3D Lepto-Hadronic Internal Shock model

Example case: Magnetic energy dissipation (reducing B-field, additional e and p injection)

(Zhang et al. 2016)

Snap-Shot SEDs

Pol. Deg. vs. Photon Energy
PA swings in hadronic models

MW Light Curves

Pol. vs. time

(Zhang et al. 2016)
PA swings in hadronic models

High-energy (p-sy) polarization signatures much more stable than low-energy (e-sy) signatures, due to slower p cooling:

No PA swings in X-rays – γ-rays!

(Zhang et al. 2016)
Summary

1. X-ray / $\gamma$-ray polarimetry of blazars may help answer several outstanding questions:
   a) X-ray – optical co-spatiality?
   b) Mode of particle acceleration (shocks vs. magnetic reconnection)
   c) Leptonic vs. hadronic emission
   d) Nature and origin of “big blue bump” / soft X-ray excess

2. Optical spectropolarimetry + SED modeling tightly constrains unpolarized emission components (e.g., accretion disk) → Measure BH mass

3. Optical PA swings may be modeled with straight shock-in-jet model with helical magnetic fields

4. If PA swings are also present in X-rays, potential problem for X-ray polarimetry of blazars

5. In hadronic models, optical PA swings may not be mirrored in high-energy polarization.

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Thank you!

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