Models of the SEDs and Variability of Blazars

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1. Phenomenology of Blazars
2. Jet Model of Blazars
3. X-ray Spectra and Variability of Blazars
Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio jets, often with superluminal motion
- Radio and optical polarization
Blazar Classification

Intermediate objects:

Low-frequency peaked BL Lacs (LBLs):
- Peak frequencies at IR/Optical and GeV gamma-rays
- Intermediate overall luminosity
  - Sometimes γ-ray dominated

High-frequency peaked BL Lacs (HBLs):
- Low-frequency component from radio to UV/X-rays, often dominating the total power
- High-frequency component from hard X-rays to high-energy gamma-rays
Leptonic Blazar Models

Relativistic jet outflow with $\Gamma \approx 10$

Injection, acceleration of ultrarelativistic electrons

$Q_e(\gamma, t)$

Injection over finite length near the base of the jet.

Additional contribution from $\gamma \gamma$ absorption along the jet.

Synchrotron emission

Compton emission

Seed photons:
- Synchrotron (SSC)
- External Sources (EC)
Sources of External Photons

Direct accretion disk emission

Optical-UV Emission from the Broad-line Region (BLR)

Infrared Radiation from the Obscuring Torus

Synchrotron emission from other regions of the jet
Quasi-Equilibrium Electron Distributions

Balance injection of a power-law distribution of relativistic electrons with radiative cooling and escape from the emission region:

\[ t_{\text{esc}} = \eta \frac{R}{c} \]

\[ \frac{d\gamma}{dt} = -\nu_0 \gamma^2 \]

\[ t_{\text{cool}} = \frac{\gamma}{|d\gamma/dt|} = \frac{1}{(\nu_0 \gamma)} \]

→ Spectral break at \( \gamma_c \), where \( t_{\text{esc}} = t_{\text{cool}} \)

\[ \gamma_c = \frac{c}{(\eta R \nu_0)} \]

Compton cooling in KN regime
Spectral Variability

Spectral Evolution of a Blazar Flare

Simulation

\[ EF_E \text{ [Jy Hz]} \]

Frequency [Hz]

1e+12 1e+14 1e+16 1e+18 1e+20 1e+22 1e+24 1e+26
Spectral Variability

Mrk 421

Hardness-Intensity Diagrams

Spectral Time Lags

(Takahashi et al. 1996)
Parameter Constraints from Observations of Spectral Variability

If energy-dependent (spectral) time lags are related to energy-dependent synchrotron cooling time scale:

\[ \frac{d\gamma}{dt} = -\nu_0 \gamma^2 \quad \text{with} \quad \nu_0 = \frac{4}{3} c \sigma_T u'_B \]

\[ t_{\text{cool}} = \frac{\gamma}{|d\gamma/dt|} = \frac{1}{(\nu_0 \gamma)} \]

and

\[ \nu_{\text{sy}} = 3.4 \times 10^6 (B/G) (D/(1+z)) \gamma^2 \text{ Hz} \]

=> \[ \Delta t_{\text{cool}} \sim B^{-3/2} (D/(1+z))^{1/2} (\nu_1^{-1/2} - \nu_2^{-1/2}) \]

=> Measure time lags between frequencies \( \nu_1, \nu_2 \rightarrow \)
estimate Magnetic field (modulo D/[1+z])!
Spectral modeling results along the Blazar Sequence: Leptonic Models

High-frequency peaked BL Lac (HBL):

- No dense circumnuclear material → No strong external photon field
- Low magnetic fields (~ 0.1 G);
- High electron energies (up to TeV);
- Large bulk Lorentz factors ($\Gamma > 10$)

The “classical” picture

(Petry et al. 2000)
Spectral modeling results along the Blazar Sequence: Leptonic Models

Radio Quasar (FSRQ)

- High magnetic fields (~ a few G);
- Lower electron energies (up to GeV);
- Lower bulk Lorentz factors ($\Gamma \sim 10$)

Plenty of circumnuclear material $\rightarrow$ Strong external photon field

- **Synchrotron**
- **External Compton**

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![Graph of 3C279 with data points and curves indicating synchrotron and external Compton emissions.](image)
Modeling Mrk421

\[ L_e = 4.5 \times 10^{43} \text{ erg/s} \]
\[ \gamma_1 = 2.5 \times 10^4 \]
\[ \gamma_2 = 4.0 \times 10^5 \]
\[ q = 2.5 \]
\[ R = 3 \times 10^{15} \text{ cm} \]
\[ D = 30 \]
\[ B = 0.37 \text{ G} \]
\[ L_B = 4.2 \times 10^{42} \text{ erg/s} \]
\[ \varepsilon_B = 0.093 \]
Variability Modeling

Mrk 421
April 30, 2006
Hardness-Intensity Correlation

Mrk 421
Hardness-Intensity Diagram at 1 keV
X-Ray Variability of the FSRQ 3C279
X-Ray Variability of the FSRQ 3C279

X-ray flux and spectrum virtually unchanged in spite of huge variability in the optical!
Spectral Modeling of 3C279

All three low-X-ray states modeled with only changing $\gamma_{\text{min}}$!

- $\gamma_{\text{min}} = 550$
- $\gamma_{\text{min}} = 750$
- $\gamma_{\text{min}} = 1500$
X-ray Spectral Variability of a Generic FSRQ
Summary

• Snap-shot X-ray spectra of HBLs (e.g., Mrk 421) and FSRQs are usually well described by featureless power-laws.
• However, HBLs show rapid (intraday) variability in flux and **spectral shape**!
• FSRQs are fainter X-ray sources, but X-ray spectra are more stable, with moderate spectral variability on time scales of ~ days.