An Internal Shock Model for the Variability of Blazar Emission

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Blazars

• Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
• Rapidly (often intra-day) variable
Blazar Variability: Example: The Quasar 3C279

(Böttcher et al. 2007)
**Blazar Variability:**

**Example:** The BL Lac Object 3C66A

(Böttcher et al. 2009)

Optical Variability on timescales of a few hours.
Blazar Variability: Variability of PKS 2155-304

VHE γ-rays and X-ray variability often closely correlated

VHE γ-ray variability on time scales as short as a few minutes!

(Costamante et al. 2008)
Spectral Variability

Hardness-Intensity Diagrams

Spectral Time Lags

(Mrk 421; Takahashi et al. 1996)
Blazars

• Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
• Rapidly (often intra-day) variable
• Strong gamma-ray sources
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 – γ-rays)
• 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

Quasars:
- Low-frequency component from radio to optical/UV
- High-frequency component from X-rays to g-rays, often dominating total power
- Peak frequencies lower than in BL Lac objects (Hartman et al. 2000)

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

Intermediate objects:
- Low-frequency peaked BL Lacs (LBLs):
  - Peak frequencies at IR/Optical and GeV gamma-rays
  - Intermediate overall luminosity
  - Sometimes γ-ray dominated (Boettcher & Reimer 2004)

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

Injection over finite length near the base of the jet.

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

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

Synchrotron emission

Compton emission

$Q_e(\gamma, t)$

$\gamma^{-q}$
Spectral Variability

Hardness-Intensity Diagrams

Spectral Time Lags

(Takahashi et al. 1996)
Interpretation of Spectral Variability in Blazars

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

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

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

\[ \Rightarrow \text{Measure time lags between frequencies } \nu_1, \nu_2 \]

\[ \rightarrow \text{estimate Magnetic field (modulo } D/[1+z])! \]
The simplest version assumes that the emission region is spherical ...
Problems of spherical, homogeneous models

If the entire SED is produced by the same electron population, variability at all frequencies should be well correlated – but …

1ES 1959+650 (2002)

PKS 1510-089 (2008 - 2009)

(Krawczynski et al. 2004)

(Marscher et al. 2010)
Problems of spherical, homogeneous models

Cross-correlations between frequency bands and time lags do not show a consistent picture

3C454.3 (2007): AGIlE $\gamma$-rays vs. R-band

=> Possible $< 1$ day delay (hard lag) of $\gamma$-rays behind R-band (?)

S5 0716+714 (2006): Optical B vs. R band

=> $\sim 35$ minute delay (soft lag) of R vs. B band

(discrete correlation function plot)

(Donnarumma et al. 2007)

(Wu et al. 2010)
The Internal Shock Model for Blazars

(Böttcher & Dermer 2010)

The central engine ejects two plasmoids \((a,b)\) into the jet with different, relativistic speeds (Lorentz factors \(\Gamma_b >> \Gamma_a\))

\[
\Gamma_b \quad \Gamma_a
\]

Shock acceleration

\[Q(\gamma) = Q_0 \gamma^{-q} \quad \text{for} \quad \gamma_1 < \gamma < \gamma_2\]

\(\gamma_2\) from balance of acceleration and synchr. Cooling rate

\(\gamma_1\) from normalization to overall energetics
Time-Dependent Electron Distributions

Competition of injection of a power-law distribution of relativistic electrons with radiative cooling

At any given time $t_{em}(x) = \text{time elapsed since the shock has crossed a given point } x$

$$\frac{d\gamma}{dt} = -v_0 \gamma^2$$

$$t_{\text{cool}} = \frac{\gamma}{|d\gamma/dt|} = \frac{1}{v_0 \gamma}$$

$\rightarrow$ Spectral break at $\gamma_c$, where $t_{em}(x) = t_{\text{cool}}$

$$\gamma_{\text{min}} = \left(\gamma_1^{-1} + v_0 t\right)^{-1}$$
Radiation Mechanisms

1) Synchrotron

\[ \nu F_{\nu}(\epsilon, t_{\text{obs}}) = \frac{D^4 \pi R^2}{d_L^2} \int_{\bar{x}_{\text{min}}}^{\bar{x}_{\text{max}}} \bar{\epsilon} j_{\bar{\epsilon}}(\bar{x}, \bar{t}_{k,\text{em}}) \, d\bar{x} \]

\[ B_{f,r} = \sqrt{8\pi r \epsilon_B \left( \Gamma_{f,r}^2 - \bar{\Gamma}_{f,r} \right) n'_{a,b} m_p c^2} \]

Delta-function approximation for synchrotron emissivity:

\[ j_{\bar{\epsilon},\text{sy}} = \frac{c \sigma_T B^2 \bar{\epsilon}}{48\pi^2 b^2 \gamma_{\text{sy}}} n_e(\gamma_{\text{sy}}) \]

\[ \Rightarrow \nu F_{\nu}^{\text{sy}} (t_{\text{obs}}) \]

can be calculated fully analytically!
Radiation Mechanisms (contd.)

2) External-Compton

Delta-function approximation for Compton cross section:

\[
\frac{d\sigma}{d\epsilon_c d\Omega_c} \approx \sigma_T \delta(\epsilon_c - \gamma^2 [1 - \beta\mu_c] \epsilon_s) \delta(\Omega_c - \Omega_e) H(1 - \gamma \epsilon_s [1 - \beta\mu_c]).
\]

Assume mono-energetic, isotropic external radiation field

\[
\Rightarrow \nu F^\text{EC}_\nu (t_{\text{obs}})
\]

can be calculated fully analytically!
3) Synchrotron-Self Compton

Emissivity with delta-function approximation for the Compton cross section:

\[ j_{\epsilon,SSC}(\vec{x}, \bar{t}_{x,em}) \approx \frac{c \sigma_T m_e c^2}{8\pi} \frac{1/(\epsilon[1-\mu_c])}{\epsilon^{1/2}} \int \frac{d\Omega_s}{4\pi} \int_{0}^{\infty} d\epsilon_s \sqrt{1-\mu_c} \frac{n_{ph}(\epsilon_s, \bar{\Omega}_s, \bar{x}, \bar{t}_{x,em})}{\epsilon_s^{1/2}} n_e(\gamma_c; \bar{x}, \bar{t}_{x,em}) \]

\[ => n_{ph}^{sy}(\epsilon_s, x, t) = \]

Integral over the retarded synchrotron photon distributions from all shocked regions of the jet!

\[ n_{ph}^{sy}(\epsilon_s, x, t) \]

can be calculated fully analytically

\[ => \text{Two integrations to be done numerically.} \]
Baseline Model
Parameters / SED characteristics typical of FSRQs or LBLs
Baseline Model

Snap-shot SEDs and time-averaged SED over 30 ksec
Baseline Model

Light Curves
Baseline Model

Discrete Correlation Functions

X-rays lag behind HE $\gamma$-rays by $\sim 1.5$ hr

Optical leads HE $\gamma$-rays by $\sim 1$ hr

Optical leads X-rays by $\sim 2$ hr
Parameter Study
Varying the External Radiation Energy Density

SED Characteristics

IBL  LBL  FSRQ
Parameter Study

Varying the External Radiation Energy Density

DCF's / Time Lags

Reversal of time lags!
Parameter Study

Varying the External Radiation Energy Density

SED Characteristics

![Graph showing the relationship between peak frequency and peak flux with varying q values.]
Parameter Study

Varying the External Radiation Energy Density

DCF$s$ / Time Lags

Reversal of time lags!
Summary

• We developed a semi-analytical internal shock model for blazars: Synchrotron + EC analytical; SSC: 2 numerical integrations.

• Appropriate to reproduce SEDs of FSRQs and LBLs

• Predicts optical lead before higher-energy emission by 1 – 2 hours

• Magnitude and sign of time lags sensitive to various poorly constrained parameters.