Variability Patterns in Inhomogeneous Jets with Particle Diffusion and Localized Acceleration

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Recent Results in Astrophysics
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Outline

- Introduction and model setup
- Steady State Spectrum
- Variability Analysis
Active Galactic Nucleus (AGN)

Jet moving relativistically

Blazars: Along the Jet

(Credit: Urry & Padovani)
Ultra-fast flares
– small emission region ($10^{-4}$ pc)

(PKS 2155-304, Aharonian et al. 2007)
Coincidence of flares and radio events
- far away emission region (~ pc scale)

(PKS 1510-089, Marscher et al. 2010)
2nd order Fermi Acceleration
Through the continuity equation:

$$\frac{\partial n(\gamma, \mathbf{r}, t)}{\partial t} = -\frac{\partial}{\partial \gamma} \left[ n(\gamma, \mathbf{r}, t) \dot{\gamma}(\gamma, \mathbf{r}, t) \right]$$

$$+ \frac{\partial}{\partial \gamma} \left[ D(\gamma, \mathbf{r}, t) \frac{\partial n(\gamma, \mathbf{r}, t)}{\partial \gamma} \right] + Q(\gamma, \mathbf{r}, t)$$

$$- \nabla \cdot \left[ D_x(\gamma) \nabla n(\gamma, \mathbf{r}, t) \right].$$

Spatial diffusion of particles

(Chen et al. 2011)
Radiation: Monte Carlo Comptonization

- Synchrotron radiation
- Synchrotron Self-Comptonization including light travel time effects (LTTEs)

Homogeneous magnetic field used in this study

Observer. Relativistic beaming
Outline

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• Variability Analysis
Accelerator in the center
--Electron energy density map evolution
the acceleration region occupies 2x2 zones
Steady State

Accelerator in the center

--Electron energy distribution (EED) of individual cells

Inner cell

Mid cell

Outer cell
Steady State

Accelerator in the center

--Total EED and SED

SSC spectrum harder than synchrotron spectrum

Spectral Index
-0.71
-0.63
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• Introduction and model setup
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Amplitude: quadratic or linear?  
Time: lag or no lag?  

(Fossati et al. 2008)
Power Spectrum Density (PSD)

Power-law without any break

\[ |F_N(\nu)|^2 = \left[ \sum_{i=1}^{N} f_i \cos(2\pi \nu t_i) \right]^2 + \left[ \sum_{i=1}^{N} f_i \sin(2\pi \nu t_i) \right]^2 \]

\[ P(\nu) = \frac{2T}{\mu^2 N^2} |F_N(\nu)|^2 \]

Observation

Average Fermi PSD, for 9 brightest FSRQs

(Chatterjee et al. 2012)

(Abdo et al. 2010)
Fourier Transform of the Fokker-Planck equation

\[
\frac{\partial N_e}{\partial t} + \frac{\partial}{\partial \gamma} \left[ \gamma(\gamma, t) N_e(\gamma; t) \right] + \frac{N_e(\gamma; t)}{t_{\text{esc}}(\gamma, t)} = Q(\gamma, t)
\]

\[-2\pi i f \tilde{N}_e(\gamma, f) + \frac{\partial}{\partial \gamma} \left[ \gamma(\gamma) \tilde{N}_e(\gamma, f) \right] + \frac{\tilde{N}_e(\gamma, f)}{t_{\text{esc}}(\gamma)} = \tilde{Q}(\gamma, f)\]

- Existing model

- Synchrotron

- SSC

\[S(\gamma, f) \propto f^{-a} \quad (f < 1/t_{\text{cool}})\]

\[S(\gamma, f) \propto f^{-(a+2)} \quad (f > 1/t_{\text{cool}})\]

(Finke & Becker 2014)
Many (e.g., 169) turbulent cells across jet cross-section, each followed after crossing shock, where e-’s are energized & Compton scatter seed photons from dusty torus & Mach disk*; each cell has its own uniform magnetic field selected randomly from turbulent power spectrum + its own e- population

*Plan to add seed photons from emission-line clouds alongside the jet (Isler et al. 2013, León-Tavares et al. 2012) & SSC from other cells

(talk by Alan Marscher 2015)
Power Spectra of Polarization Variations of Simulation

Existing model

Flux Power spectrum slope -1.6 to -2.3 on long time-scales (low variational frequencies), flattens on shorter time-scales

Stokes parameters: Power spectrum slope \( \sim -1.6 \) on short time-scales (high variational frequencies), flattens on longer time-scales

Break frequency higher for more turbulent field (talk by Alan Marscher 2015)
Random Acceleration along the spine

--Electron energy density map evolution
Random Acceleration along the spine
– EED and SED
Random acceleration

**Power Spectral Density**
- **Slope = -2**
  - 1 eV – 3 eV
  - 2 keV – 4 keV
  - 9 keV – 15 keV
  - 0.3 TeV – 10 TeV

**Cross correlation function**
- 0.3 TeV – 10 TeV lags
- 2 keV – 4 keV lags

- **Quadratic**
- **Red noise**
- **Light crossing time scale**
- **Acceleration decay time scale**
- **X-ray cooling time scale**

**No lags?**
Random acceleration

Power Spectral Density

- Red noise
- Light crossing time scale
- Acceleration decay time scale
- X-ray cooling time scale

Quadratic

No lag?
Assumptions

1. Simulation length $T'/\Gamma = 9 \times 10^5$ ks;

2. Every time step (0.5 ks) each cell has 7% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of $t'/\Gamma = 20$ ks;

4. Particle injection (at $\gamma = 33$) increases with acceleration rate.
White Noise vs. Red Noise

\[ F_t = \text{random}(-0.5, 0.5) \]

\[ F_{t+1} = F_t + \text{random}(-0.1, 0.1) \]
PSD Basics, no astrophysics!

PSD with break

\[ F_{t+1} = F_t \times \exp(-\Delta t/T) + \text{random}(-0.1,0.1) \]

Power Spectral Density

Decay 1/T

Longer data sample

Power Spectral Density

Decay 1/T
1. Simulation length $T'/\Gamma = 9 \times 10^5 \, 3.5 \times 10^6 \, s$;

2. Every time step (0.5ks) each cell has 7% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of $t'/\Gamma = 20 \, ks$;

4. Particle injection (at $\gamma = 33$) increases with acceleration rate;
3.5 Ms long simulation

Is there a break?

γ-ray lags
1. Simulation length $T'/\Gamma = 9 \times 10^5$ ks.

2. Every time step (0.5 ks) each cell has 7%–14% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of $t'/\Gamma = 20$ ks;

4. Particle injection (at $\gamma = 33$) increases with acceleration rate;
Higher acceleration frequency

No significant change
1. Simulation length $T'/\Gamma=9 \times 10^5$ ks;

2. Every time step (0.5 ks) each cell has 7% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of $t'/\Gamma=20$ 40 ks;

4. Particle injection (at $\gamma=33$) increases with acceleration rate.
Slower Acceleration decay

No significant change
1. Simulation length $T'/\Gamma = 9 \times 10^5$ ks;

2. Every time step (0.5 ks) each cell has 7% chance for additional acceleration (accumulating);

3. Acceleration decay on time scale of $t'/\Gamma = 20$ ks;

4. Particle injection (at $\gamma = 33$) increases does not increase with acceleration rate.
No injection variation

little optical variability

Linear

Small lag, LTTE?
Summary

- Random acceleration produces light curves that qualitatively resemble the observed light curves in blazars;

- PSD appears to be featureless red noise;

- The amplitude relation between synchrotron and IC flux is dependent on the variability in lower energy bands;

- Variation in IC generally lags those in synchrotron.
No injection variation, acceleration varies in $\Gamma'/\Gamma=5 \text{ ks}$
3.5 Ms long simulation

Is there a break?

γ-ray lags
Higher acceleration frequency
Slower Acceleration decay

**Power Spectral Density**

- 1 eV – 3 eV
- 0.5 GeV – 50 GeV
- 0.3 TeV – 10 TeV
- 2 keV – 4 keV
- 9 keV – 15 keV
- slope = -2

**Cross correlation function**

- 0.3 TeV – 10 TeV lags
- 2 keV – 4 keV lags