Time-Dependent, Multi-Wavelength Models for Active Flares of Fermi Blazars

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**Confined Acceleration + Radiation Zones**

**M87** (Harris & Krawczynski 2006)

- **Right**: Schematic of our blazar model geometry, consisting of a region proximate to the shock that is the acceleration (injection) zone which is embedded in a much larger radiation zone.
- Also depicted is a turbulent field, signified by the red field line projections.
Numerical Scheme

- Injection spectra $Q_e(\gamma,t')$ from turbulence characteristics + MC simulations of DSA
- Injection from small acceleration zone (shock) into larger radiation zone
- Time-dependent leptonic code based on Böttcher & Chiang (2002)
- Radiative processes:
  - Synchrotron
  - Synchrotron self-Compton (SSC)
  - External Compton (EC: dust torus + BLR + direct accretion disk)

$$Q_e(\gamma,t') = Q_e(\gamma) \ H(t' ; 0, \ Dt'), \text{ primes denoting comoving jet frame.}$$

Shock injection “on” for $0 < \Delta t' < L'/v'_s$
The acceleration timescale for electrons is short: it scales as the cyclotron period (for shock drift and diffusive acceleration):

$$t_{\text{acc}} \sim \eta t_{\text{cyc}} = \eta \frac{2\pi \gamma \beta m_e c}{e B} \ll t_{\text{cool}}, \ t_{\text{dyn}}$$

for most electrons, i.e. those below around 300 MeV in blazars.

- For time evolution of blazar flares, we therefore use a shock-acceleration electron distribution (from Summerlin & Baring 2012) as an instantaneous injection $Q_e(\gamma)$.

- Then solve a Fokker-Planck equation for electron distribution evolution in the jet frame:

$$\frac{\partial n_e}{\partial t'} = -\frac{\partial}{\partial \gamma} \left( \gamma n_e \right) + Q_e(\gamma, t') - \frac{n_e}{t_{\text{esc}}} \quad \text{for} \quad n_e \equiv n_e(\gamma, t').$$

This includes competition between acceleration and cooling.
One-zone Multiwavelength SSC fits to BL Lacertae

- SSC explains X-rays but cannot fit gamma-rays; EC component added.
- Large $\eta$ ($\sim 10^7$) needed to move synchrotron peak into optical (for LBLs).


$z = 0.069$

$\eta_1 = 20$

$\alpha = 3$

$\eta(p) = \lambda/r_g \sim \eta_1 (p/mc)^{\alpha-1}$
FSRQ 3C279

Extended flaring period 2013 – 2014

Variability time scale ~ 1 day

(Hayashida et al. 2015)
Shock Injected and Cooled Electrons

The non-thermal particle spectral index and thermal-to-non-thermal normalization from Monte Carlo acceleration simulations are strongly dependent on $\eta_1 (=100$ in the figure) and $\alpha (=3$ in figure).

$$\eta(p) = \frac{\lambda}{r_g} \sim \eta_1 \frac{(p/mc)^{\alpha-1}}{\nu}$$
Evolving MW Spectra during 3C 279 flares – Dec 2013-Apr 2014

- Time evolution of MW spectra for 3C 279 during strong flares in January 2014.
- Model curves are derived for flare C only, with different times during a flare corresponding to different colors and linestyles.

\[ \Gamma = 15, \ B' = 0.65 \text{ Gauss} \]
**3C 279: Time Evolution Models for Flare C**

- **Left panel**: Model time traces of $\nu F_\nu$ fluxes displaying various delays in radio to gamma-ray wavebands during Flare C. Onset of injection is at $t=0$.

- **Right panel**: Evolutionary traces in the spectral index/flux plane with time directions as indicated. The different wavebands are labeled by their components: synchrotron, SSC and external Compton. Spectral hysteresis assumes a characteristic counter-clockwise form.
3C 279: *Fermi*-LAT light curves

- Periods B and D suggest possibly asymmetric injection of duration close to GeV cooling timescales (1-3 hours)
Conclusions

- **Broadband blazar spectra**: X-ray/γ-ray diagnostics on turbulence power spectra and particle diffusion.
  - Details in Baring, Böttcher & Summerlin (MNRAS 464, 4875, 2017)

- **Coupled Monte Carlo Simulations** of diffusive shock acceleration and radiation transport reveal strongly energy-dependent mean-free-path to scattering.
  - MW fits demand $\eta = \lambda / r_g$ to be an increasing function of $p$ as scales sample greater distances from the shock.

- **3C 279** (an LBL) presents a particular temporal case:
  - Hardness/flux evolution displays characteristic counter-clockwise spectral hysteresis in all bands.
  - X-rays and radio are well-correlated, but lag optical and γ-rays by about 5-9 hours. => comparative cooling times.
  - Different lags/hysteresis are expected for other blazar types.

- **Spectroscopy and evolution present consistency in model parameter determination.**

- **Next test**: modeling hard Fermi-LAT Flare B.
**DCF** measures relative fluxes between different bands.

- Optical and γ-rays **well correlated** (0 lag). X-rays and radio **well correlated** (0 lag).
- X-rays and radio **lag** optical + γ-rays by **5-9 hrs**, latter being generated by higher energy electrons, and therefore possessing a shorter response (cooling) time.

The discrete correlation function is

\[
C_{a,b}(\tau) \equiv \frac{1}{N_a N_b} \int_{-\infty}^{\infty} F_a(t) F_b(\tau - t) \, dt
\]

for fluxes \(F_{a,b}\) in wavebands a,b, with

\[
N_a = \int_{-\infty}^{\infty} F_a(t) \, dt
\]

defining the normalizations.

One-zone Multiwavelength SSC fits to Mrk 501

- Synchrotron explains X-rays but cannot fit optical/UV; galaxy component added.
- Large $\eta$ ($\sim 10^4$) needed to move synchrotron peak $E_{\text{max}} \sim m_e c^2 / (\eta \alpha_f)$ into X-rays.
- Need for large $\eta=\lambda/r_g$ in blazars identified by Inoue & Takahara (1996).

**Baring, Boettcher & Summerlin (2017, MNRAS): steady-state models only**

\[ z=0.034 \]

\[ \eta_1 = 100 \]

\[ \alpha = 3/2 \]
Shock Acceleration Injection Efficiencies

\( \eta(p) = \frac{\lambda}{r_g} \sim \eta_1 \left( \frac{p}{mc} \right)^{\alpha-1} \)

Baring et al. (MNRAS, 2017)

- The non-thermal particle spectral index and thermal-to-non-thermal normalization from Monte Carlo acceleration simulations are strongly dependent on \( \eta_1 \) (≈ 3,100 in the figure) and \( \alpha \) (≈ 1/2, 2 in figure), and the B-field obliquity to the shock normal!
Constraining SSC fit Parameter $\eta = \lambda_///r_g$

- Large $\eta$ needed to move synchrotron peak $E_{\text{max}} \sim m_e c^2/(\eta \alpha_f)$ into X-rays.
• Inertial range can span 1-5 orders of magnitude.
• Doppler gyro-resonance condition $\omega = \Omega / \gamma$ may not be satisfied by charges with large gyroradii;
• $\Rightarrow$ increase of diffusive mean free path parameter $\eta = \lambda / r_g$ at large momenta.
• Expect $\lambda \propto p^2$ at long wavelengths, below stirring scale (QLT).