Modeling Blazar SEDs and Spectral Variability with Time-Dependent Diffusive Shock Acceleration: Application to 1ES 1959+650 Observed with AstroSAT

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Relativistic Shocks in Jets

- Internal Shocks: likely sites of relativistic particle acceleration.
- Most likely mildly relativistic, $\beta \gamma \sim 1$
- In most works: Simple power-law or log-parabola electron spectra (from Fermi I / II acceleration) assumed with spectral index ($\sim 2$) put in “by hand”.

Jet of M87 at different wavelengths
Monte-Carlo Simulations of Diffusive Shock Acceleration (DSA)

- Gyration in B-fields and diffusive transport (pitch-angle diffusion) modeled by a Monte Carlo technique.

- Shock crossings produce net energy gains $\rightarrow$ first-order Fermi.

- Pitch-angle diffusion parameterized through a mean-free-path ($\lambda_{\text{pas}}$) parameter $\eta (p)$:

$$\lambda_{\text{pas}} = \eta(p) r_g \sim p^\alpha \quad (\alpha \geq 1)$$

(Summerlin & Baring 2012)
Shock Acceleration Spectra

Non-thermal particle spectral index and thermal-to-non-thermal normalization are strongly dependent on $\eta_0$, $\alpha$, and B-field obliquity!

Particle spectra as hard as $n(\gamma) \sim \gamma^{-1}$ possible!

Baring et al. (2017)
Constraints from Blazar SEDs

Synchrotron peak $\leftrightarrow \gamma_{\text{max}}$

Balance $t_{\text{acc}} \sim \eta(\gamma) \omega_{\text{gyr}}(\gamma)^{-1}$
with radiative cooling time scale

If synchrotron cooling dominates:

$$\gamma_{\text{max}} \sim B^{-1/2} [\eta(\gamma_{\text{max}})]^{-1/2}$$

$$\Rightarrow h\nu_{\text{sy}} \sim 100 \delta [\eta(\gamma_{\text{max}})]^{-1} \text{ MeV} \quad \text{(independent of B-field!)}$$
Constraints from Blazar SEDs

\[ h\nu_{\text{sy}} \sim 100 \delta [\eta(\gamma_{\text{max}})]^{-1} \text{ MeV} \quad (\text{independent of B-field!}) \]

\[ \Rightarrow \text{Need large } \eta(\gamma_{\text{max}}) \text{ to obtain synchrotron peak in optical/UV/X-rays} \]

\[ \Rightarrow \text{But: Need moderate } \eta(\gamma \sim 1) \text{ for efficient injection of particles into the non-thermal accelerations scheme} \]

\[ \Rightarrow \text{Need strongly energy dependent pitch-angle scattering m.f.p., with } \alpha > 1 \text{ (Baring et al. 2017)} \]
Implications for Shock-Induced Turbulence

Gyro-resonance condition: \( \lambda_{\text{res}} \propto p \)

\( \Rightarrow \) Higher-energy particles interact with longer-wavelength turbulence

\[ k_{\text{stir}} \sim \frac{2\pi}{R} \]

Stirring Scale \( \sim R \)

Inertial Range

Dissipation Scale

Turbulence level decreasing with increasing distance from the shock

\( \Rightarrow \) High-energy (large \( r_g \)) particles “see” reduced turbulence

\( \Rightarrow \) Large \( \lambda_{\text{pas}} \)
Electron Evolution Time Scales

Mrk 501

- SSC
- Synchrotron
- Total rad. cooling
- $t_{\text{dyn}} = R/c$
- $t_{\text{esc}} = \eta_{\text{esc}} \times t_{\text{dyn}}$
- $t_{\text{acc}}$

$v_F$ [Jy Hz]

$\nu$ [Hz]
Time-Dependent Electron Evolution with Radiative Energy Losses

Acceleration time scale:

\[ t_{\text{acc}} = \eta \ t_{\text{gyr}} = \eta \ \frac{2\pi \gamma m_e c}{eB} \ll t_{\text{cool}}, t_{\text{dyn}} \]

For almost all electrons

⇒ Use shock-accelerated electron spectrum as instantaneous injection \( Q_e(\gamma) \);
⇒ Solve Fokker-Planck Equation for electrons:

\[
\frac{\partial n_e(\gamma,t)}{\partial t} = - \frac{\partial}{\partial \gamma} (\gamma \ n_e) + Q_e(\gamma,t) - \frac{n_e(\gamma,t)}{t_{\text{esc,e}}} 
\]
Numerical Scheme

- Injection spectra 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)

Shock injection “on” for
\[ 0 < \Delta t' < L'/v'_s \]

\[ Q_{e,s}(\gamma,t') = Q_{e,s}(\gamma) H(t'; 0, \Delta t') \]
Example: HBL 1ES 1959+650

- Prototypical HSP BL Lac object at $z = 0.048$
- Observed with AstroSAT during flaring states in 2 long (144 ksec) observations in 2016 and 2017

(Chandra et al. 2021)
Example: HBL 1ES 1959+650

- Pronounced spectral variability (harder when brighter)
- Log-parabolic spectral fits: \( F_E \sim E^{-(\alpha + \beta \log[E/E_0])} \)

(Chandra et al. 2021)
1ES 1959+650 in 2016

Complex variability patterns require passage of multiple shocks.

\[ \lambda_{\text{pas}} = 60 \ r_g \ \gamma^{0.9} \]

\[ \eta_1 = 60 \]

\[ \alpha = 1.9 \]

\[ B = 0.15 \ \text{G} \]

\[ \delta = 20 \]

\[ R = 6 \times 10^{15} \ \text{cm} \]

\[ \rightarrow \Delta t' \sim 2 \times 10^5 \ \text{s} \]

\[ \rightarrow \Delta t_{\text{obs}} \sim 2.8 \ \text{h} \]

Flaring caused by
- increasing \( L_{\text{inj}} \)
- decreasing \( \eta_0 \)
2016: MWL Light Curves

<table>
<thead>
<tr>
<th>Parameter [units]</th>
<th>( L_{\text{inj}} ) [erg/s]</th>
<th>( \eta_0 )</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quiescence</td>
<td>( 2.5 \times 10^{40} )</td>
<td>60</td>
<td>1.9</td>
</tr>
<tr>
<td>Shock 1</td>
<td>( 3.0 \times 10^{40} )</td>
<td>50</td>
<td>1.9</td>
</tr>
<tr>
<td>Shock 2</td>
<td>( 3.5 \times 10^{40} )</td>
<td>50</td>
<td>1.9</td>
</tr>
<tr>
<td>Shock 3</td>
<td>( 4.1 \times 10^{40} )</td>
<td>40</td>
<td>1.9</td>
</tr>
<tr>
<td>Shock 4</td>
<td>( 3.4 \times 10^{40} )</td>
<td>50</td>
<td>1.9</td>
</tr>
</tbody>
</table>

(Chandra et al. 2021)
2016: Discrete Correlation Functions

Strong correlations between X-rays and VHE \( \gamma \)-rays

Soft X-ray lags of \(~ 1 \) hour behind hard X-rays and VHE \( \gamma \)-rays.

(Chandra et al. 2021)
2016: Hardness-Intensity Diagrams

1ES 1959+650
2016 - Hardness-Intensity Diagrams

Harder-when-brighter trend without significant spectral hysteresis is well reproduced.

(Chandra et al. 2021)
1ES 1959+650 in 2017

Higher flux state well reproduced by changing Doppler factor (smaller viewing angle $\theta_{\text{obs}}: 2.87^\circ \rightarrow 2.34^\circ$)

$\lambda_{\text{pas}} = 40 \ r_g \ \gamma^{0.8}$

$\eta_1 = 40$
$\alpha = 1.8$
$B = 0.08 \text{ G}$
$\delta = 24$
$R = 10^{16} \text{ cm}$
$\Rightarrow \Delta t' \sim 3 \times 10^5 \text{ s}$
$\Rightarrow \Delta t_{\text{obs}} \sim 3.9 \text{ h}$

Flaring caused by
- increasing $L_{\text{inj}}$
- decreasing $\eta_0$
- decreasing $\alpha$

(Chandra et al. 2021)
2017: MWL Light Curves

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<tr>
<td>Quiescence</td>
<td>$2.8 \times 10^{40}$</td>
<td>40</td>
<td>1.8</td>
</tr>
<tr>
<td>Shock 1</td>
<td>$3.5 \times 10^{40}$</td>
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<tr>
<td>Shock 2</td>
<td>$3.0 \times 10^{40}$</td>
<td>30</td>
<td>1.8</td>
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<tr>
<td>Shock 3</td>
<td>$3.6 \times 10^{40}$</td>
<td>25</td>
<td>1.8</td>
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<tr>
<td>Shock 4</td>
<td>$4.3 \times 10^{40}$</td>
<td>25</td>
<td>1.8</td>
</tr>
<tr>
<td>Shock 5</td>
<td>$5.1 \times 10^{40}$</td>
<td>15</td>
<td>1.8</td>
</tr>
</tbody>
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Summary


2. Time-dependent simulations of shock-in-jet model with realistic particle injection from diffusive shock acceleration, applied to long AstroSAT + MWL observations of 1ES 1959+650 in 2016 and 2017:

3. Flares with harder-when-brighter trend (no significant spectral hysteresis) well reproduced by decreasing pitch-angle-scattering mean-free path → increased turbulence levels induced by shock passage.

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Thank you!


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