Particle Acceleration at Shocks in Relativistic Jets

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- **Above**: M87 jet ($z=0.0043$) as viewed by *Chandra* (0.2-6 keV), with *VLA* 8 GHz radio contours superimposed.

- **Right**: Combined *Chandra* X-ray and *VLA* 8 GHz radio data for the PKS 1127-145 jet ($z=1.18$).

- Figures from extragalactic jet review by Harris & Krawczynski (2006, ARAA 44, 463)
Multi-wavelength Low-state SED: Fermi-LAT Blazar PKS 2155-304

$z=0.116$  Abdo et al. (2009)

HBLs vs. FSRQs; breaks in LAT-band complicate things – e.g. 3C 454.3
Particle retention in the shock layer is extremely sensitive to the magnetic field angle w.r.t. the shock normal in relativistic shocks.

**Normal Incidence Frame (NIF)       de Hoffmann-Teller frame (HT)**
Monte Carlo Simulation Particle Trajectories

- Gyration in B-fields and diffusive transport modeled by a Monte Carlo technique; color-coded in Figure according to fluid frame energy.
- Shock crossings produce net energy gains (evident in the increase of gyroradii) according to principle of first-order Fermi mechanism.

Technique devised by D. Ellison & F. Jones
Increasing upstream B-field obliquity and/or ratio of mean free path to gyroradius steepens the continuum (e.g. Bednarz & Ostrowski 1998; Ellison & Double 2004; Summerlin & Baring 2012; Kirk & Heavens 1989).
Shock Acceleration Injection Efficiencies

*Left panel:* moderately subluminal test-particle shocks;

*Right panel:* marginally subluminal test-particle shocks;

While flat distributions are realized for large $\lambda/r_g$ regimes, the price paid is a dramatic reduction in injection efficiency.

Shock Drift Acceleration in Action: $\lambda/r_g = 10^4$

- **From Summerlin & Baring (2012) - Left Panel**: projection of a selected ion orbit onto the x-y plane, exhibiting drifting in the shock layer. **Right Panel**: evolution of magnitudes of momentum in fluid ($p_F$) and shock ($p_S$) frames versus y, indicating shock drift episodes interspersed with upstream diffusive hiatuses in energy gain;

- **Lowering $\lambda/r_g$ rapidly degrades the contribution of shock drift**, enables particle convection downstream, and steepens spectrum.

- Just like shock drift acceleration in non-relativistic investigations:
Acceleration Indices: Oblique Shocks

**Left panel**: For uncooled blazar synchrotron/IC/SSC emission picture, near luminal shock regime is preferred.

**Right panel**: Cooled blazar (and GRB) scenarios require either strong turbulence, or subluminal shocks.

Multiwavelength SSC fits to Mrk 501

- Diffusive shock acceleration (DSA) with active synchrotron+IC cooling;
- Synchrotron explains X-rays but cannot fit optical; disk component added.
- Large $\eta \sim 10^4$ needed to move synchrotron peak into X-rays (for HBLs).
- Need for large $\eta = \frac{\lambda}{r_g}$ in blazars identified by Inoue & Takahara (1996).
Acceleration for variable $\eta$

- AO 0235+164 M/W fits only possible for $\eta = \lambda/r_g$ depending on $p$.
- Shock acceleration distributions exhibit breaks where $\eta$ grows beyond $10^2$.
- Physically corresponds to decline in gyroresonant interactions with turbulence on large scales.

Baring, Boettcher & Summerlin (2014)
Multiwavelength SSC/EC fits to AO 0235+164

- Diffusive shock acceleration (DSA) with active synchrotron+IC cooling;
- BL Lac object AO 0235+164 is pathological: synchrotron cannot fit X-rays;
- Bulk Comptonization by thermal population (present in DSA) appears in X-rays;
- Large $\eta$ ($\sim 10^8$) needed to move synchrotron peak to optical: $E_{\text{max}} \sim m_e c^2 / (\eta \alpha_f)$


Baring, Boettcher & Summerlin (2014)
Canonical Turbulence Power Spectrum

- Inertial range can span 1-5 orders of magnitude.
- Doppler 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).
Conclusions

- Shock acceleration particle indices depend on several parameters: field obliquity, the scattering strength or level of MHD turbulence, amount of diffusion across $B$;
- Index parameter space dichotomizes into subluminal (flat, favored for cooling models) and superluminal (steep) regimes.
- M/W blazar spectra: X-ray/γ-ray diagnostics on turbulence power spectra and particle diffusion.
- We expect $\eta = \lambda / r_g$ to be an increasing function of $p$ as scales sample greater distances from the shock.
Wind: Magnetic and Kinetic Turbulence in quiet Solar Wind at 1 AU

- Wind spacecraft power spectrum for (quiet) solar wind turbulence: 81 days, 11/15/00 – 02/01/04 in 3 sec intervals;
- Inertial range above $\sim 3 \times 10^{-5}$ Hz;
- Magnetic $<(\delta B)^2/8\pi>$ spectrum (blue) and kinetic $<\rho(\delta v)^2/2>$ power (red);
- Doppler 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.
SSC fits mandate $p$-dependent departures from Bohm diffusion

- Both AO 0235+164 and Mrk 501 M/W fits employed a mean free path that increased rapidly with electron momentum, much more rapidly than the Bohm diffusion bound of $\lambda=r_g \alpha p$.
- Specifically, the AO 0235+164 acceleration model had $\lambda=3r_g (p/p_{th})^2$ approximately, and the Mrk 501 model had $\lambda\sim 10r_g (p/p_{th})^{0.5}$. These generate the requisite $\eta=\lambda/r_g$ ratio at the maximum Lorentz factors (e.g. $\gamma_{max} \sim 10^6$ for Mrk 501).
- Momentum dependence of $\eta$ is actually expected for turbulence in the quiet solar wind (e.g. Wind magnetometer data).
- Momentum dependence of $\eta$ is also predicted from quasi-linear diffusion theory in MHD turbulence (e.g. see Forman et al. 1974).
Lepton Distributions for Strong Cooling

- **Left panel**: Electron spectra in a mildly relativistic, oblique shock for various turbulence levels ($\eta=\lambda/r_g$). Outside the acceleration zone, synchrotron cooling elicits a break, steepening the distributions above $\gamma\sim10^2$.

- **Right panel**: Sample distribution tailored for multiwavelength spectral fit to the blazar AO 0235+164, with $\gamma_{\text{max}}\sim10^4$ (large $\eta$). This distribution is realized in the comoving frame of the jet.
Template SSC Spectra for Variable $\eta = \lambda / r_g$

\begin{itemize}
  \item Cooled SSC spectra for shock acceleration with $\eta = \eta_0 \left( p / p_0 \right)^{\alpha - 1}$, with $\alpha = 2, 3$.
  \item Here $\lambda \propto p^\alpha$. Windows where synchrotron peaks and IC peaks emerge depend substantially on choice of $\alpha$, i.e. momentum dependence of $\lambda$.
  \item Spectral index in Fermi-LAT band also depends on choice of $\alpha$.
  \item $\Rightarrow$ X-ray/$\gamma$-ray diagnostics on turbulence power spectra and particle diffusion.
\end{itemize}
Fermi LAT + TeV Blazars

Abdo et al. ‘09
ApJ 707, 1310

$z = 0.44$?

$E^2 dN/dE \text{ [erg cm}^{-2} \text{s}^{-1}]$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$

$E \text{ [eV]}$

3C 66A/B

LAT

VERITAS

MAGIC

$z = 0.031$

$E^2 dN/dE \text{ [erg cm}^{-2} \text{s}^{-1}]$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$

$E \text{ [eV]}$

Mrk 421

LAT

MAGIC

VERITAS

$z = 0.034$

$E^2 dN/dE \text{ [erg cm}^{-2} \text{s}^{-1}]$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$

$E \text{ [eV]}$

Mrk 501

MAGIC

LAT

$z = 0.09-0.78$

$E^2 dN/dE \text{ [erg cm}^{-2} \text{s}^{-1}]$

$10^{-10}$

$10^{-11}$

$10^{-12}$

$10^{-13}$

$10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$

$E \text{ [eV]}$

PG 1553+113

LAT

MAGIC
The Monte Carlo simulations use a kinetic description of convection and diffusion in MHD shocks; Thermal ions and e\textsuperscript{-} are injected far upstream of shock; Particle diffusion in MHD turbulence is phenomenologically described via the mean free path $\lambda$ being proportional to some power of its gyroradius $r_g$. See next slide for a depiction. Principal advantages include addressing large momentum ranges => excellent for astrophysical problems. Simulations are fully relativistic, and not restricted to subluminal shocks, and include shock drift acceleration; Technique is well-tested in heliospheric contexts with spacecraft data Earth’s bow shock (Ellison et al. 1990) and interplanetary shocks (Baring et al. 1997; Summerlin & Baring 2006). Magnetic turbulence can be incorporated (Ostrowski et al.), though plasma effects cannot be fully modeled.