Dissipation and Particle Acceleration in Blazar Jets

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Why do blazar jets shine?

Why/how/where does (some) jet energy get converted into (nonthermal) particle pressure?
After all, magnetic acceleration is not intrinsically a dissipative process...
MAGNETIC ACCELERATION

Target: \( \frac{L_j}{\dot{M}_j c^2} \)

- **Stage 1: Magnetocentrifugal: launching the jet**
  - Brings jet to Alfvén point (\( R_A \) – basically the light cylinder) and \( \frac{1}{3} \)
  - Insensitive to streamline shape ("split monopole" model)
  - Rotational energy converted to Poynting flux

- **Stage 2: Magnetic nozzle: main acceleration stage**
  - Boosts using magnetic pressure
  - Brings jet through fast magnetosonic point and to \( \frac{1}{2} \)
  - Converts Poynting flux to kinetic energy, but …
  - \(~\)Half energy still in Poynting flux

- **Stage 3: Coasting:**
  - Near cancellation of forces further acceleration by magnetic forces (sub)logarithmic
  - Only this stage *needs* gas pressure (dissipation) to extract the last half of the energy
Relativistic acceleration is gradual (outside $R_A$)

- Inside $R_A$ energy “passes through” field lines; outside $R_A$ energy is carried by flow
- But energy has inertia: \( E = Mc^2 \)

\[ a = \frac{F}{M} \]

both numerator and denominator \( \Box \) energy content

in hydrodynamic limit,

\[ \Gamma \propto (\text{ext. pressure})^{-1/4} \]
**SOURCES OF DISSIPATION**

- **Boundary conditions**
  - Unsteady conditions at base of jet (disk connection)
  - Recollimation shocks
  - Jostle sides of jet (turbulent cocoon, intercept clouds)
  - Both are externally induced: tap unknown fraction of jet energy

- **Surface/global instabilities**
  - Kelvin-Helmholtz: suppressed as ? becomes large
  - Current-driven instabilities (kink)
    - Suppressed by poloidal field
    - Tend to wiggle whole jet

- **Internal instabilities**
  - Internal shear
  - Current-driven – not effective when jet too close to force-free
    - Need pre-existing dissipation *(see above)* to “prime pump”
CURRENT-DRIVEN INSTABILITIES

- Jets are basically moving screw-pinches
  - Helical current wound around $z$
  - Ubiquitous unstable configuration in plasma physics \textit{(Kruskal & Schwarzschild 1954)}

- Competing effects:
  - Toroidal $B_T$ is destabilizing
  - Poloidal $B_p$ is stabilizing
  - Gas pressure can enhance destabilizing effect of $B_T \text{ (MCB '98)}$

- Conclude:
  - $m=1$ (kink) most unstable
  - catalyzed by particle pressure
CURRENT-DRIVEN INSTABILITIES

• Purely magnetic (force free) jets unstable if ...
  – Poloidal field not too strong
  – Jet boundaries are “soft” (jet not too fast)

• Force-free jets enclosed in rigid walls are stable

• Conclude:
  – Best place to build up significant gas pressure is early in the acceleration process
  – Otherwise jet can be “stuck” with large Poynting flux over long distances

Plot of current density: Bromberg & Tchekhovskoy 2016
• Present when gas pressure balances toroidal field \textit{(MCB ‘98)}
• Global eigenfunction analysis confirms modes confined to annulus \textit{(Das & MCB ‘18)}
Nonlinear state: turbulence, current sheets dissipation

Pinch balanced by gas pressure: $\alpha_{\min} = 0.3$

Special relativistic MHD (Athena) simulations – O’Neill et al. 2012
How does the dissipation takes place?
First-order Fermi acceleration at shocks

- The astrophysical “standard” for ~40 years
  - Roughly the right index (for strong shocks)
  - Efficient
  - Simultaneously explain synchrotron spectra and cosmic rays
But shock acceleration doesn’t work well for:

Highly magnetized flows $\square$ shocks weak

OR

Highly relativistic flows $\square$ diffusion model (multiple shock crossings) fails

BLAZARS FAIL BOTH TESTS

(Sironi et al. 2015)
THE ALTERNATIVE: RECONNECTION

Key element in space and solar physics for decades...

... astrophysics lags behind in applying it
Why?

- Difficult to calculate
- Resistive models too slow
- Nonthermal particle acceleration inefficient at non-relativistic (Solar System) energies, particle heating instead

Picture is very different for relativistic plasmas
TEARING MODE INSTABILITY

- Tears up current sheet into filaments
- Creates magnetic “islands” (plasmoids)
- Speeds up collisional & collisionless reconnection

ALL RECONNECTION IS FAST ($\Theta 0.1 \nu_A$)
PARTICLE IN CELL SIMULATION – 2D

PARTICLE IN CELL SIMULATION – 3D w/guide field

(Cerutti et al. 2013)

(Cerutti et al. 2014)
Particle Acceleration

- Electron energy distributions develop power-law tail
- Index depends on “magnetization”

\[ \sigma = \frac{B^2}{4\pi n\bar{\gamma}mc^2} \]

- Groups using different codes agree

Sironi et al. – Princeton, CfA, Columbia
Guo et al. – Los Alamos
Werner et al. – Colorado
Power-law index (pair plasma)

- Flatter spectrum for larger $f(\gamma) \sim \gamma^{-p}$

$$\sigma = \frac{B^2}{4\pi n \gamma mc^2}$$

Guo et al. – Los Alamos

Werner et al. – Colorado
Particle energies: most energetic particles found around edges of plasmoids

Particle acceleration sites:

- between separating plasmoids
- trailing and penetrating merging plasmoids
- between merging plasmoids

(Nalewajko et al. 2015)
Electron-ion reconnection:

- Electron power-laws – similar dependence on $\sigma_i$.

\[ p_{\text{for electrons}} = 1.9 + 0.7/\sqrt{\sigma_i} \]

- e-i energy partition also depends on $\sigma_i$.

(Werner et al. 2018)
The “sweet spot” for relativistic jets?

... predicting roughly the correct observed spectral index

\[ \gamma_{\text{cutoff}} \approx 4 \left( \frac{m_i}{m_e} \right) \sigma \sim \text{few } 10^3 \]

(MHD jet acceleration gets “stuck” at \( \alpha \approx 1 \) ...

(Werner et al. 2018)
Hardens with increasing

• Empirical fit:

\[ \alpha \sim 1 + C_0 \left( \frac{\sigma \rho_e}{L} \right)^{-1/2} \]

\[ C_0 \approx 0.075 \]

THIS JUST IN: no size dependence – models converge (arXiv:1805.08754)

Zhdankin, Werner, Uzdensky, & Begelman (PRL 118, 055103 2017)
768^3 TURBULENCE SNAPSHOT FLY-THROUGH

DENSITY

CURRENT

(Zhdankin et al. 2018)
?-ray flares

Is a separate (linear accelerator) mechanism also operating?
The Crab Provides Clues

- Duration $\sim 1$ day $\sim 3 \times 10^{15}$ cm
- Photon energy $> 100$ MeV PeV electrons
- Not power-law: fit by monoenergetic spectrum
- Isotropic flare energy: $E \sim 4 \times 10^{40}$ erg

Apr 2011 Buehler+
Synchrotron emission >100 MeV challenges particle acceleration models

Under ideal MHD conditions: \( E < B \) \( \uparrow \epsilon_{\max} < 160 \text{ MeV} \)

\( \text{Radiation reaction force:} \quad F_{\text{rad}} = \frac{2}{3} r_e^2 \frac{B^2}{e^2} \)

\( \text{Accelerating force:} \quad F_{\text{acc}} = eE \)

\( \text{(Guilbert+1983, de Jager+1996, Uzdensky+2011)} \)
Speiser Orbits

- Most energetic particles: gyroradius > current sheet thickness
  - B-field field reverses during gyro-orbit
  - accelerated by $E_z$ in $z$-direction orbit stretched
  - particles become confined to current sheet

- Orbits focus towards midplane

- Midplane $B$ is small and radiation reaction is reduced

- Particles reach higher energies and emit photons with $\epsilon > \epsilon_{\text{max}}$
  
  *(Non-rel: Speiser 1965; Rel: Kirk 04, Uzdensky+ 2011)*
Evidence for relativistic Speiser orbits

Sample of 150 particle orbits

Particle beams with $E > B$: non-ideal MHD!

Particles well magnetized $\approx$ ideal MHD

(Cerutti+ 2013)
“Kinetic beaming”

- Beaming of radiation due to the strong energy-dependent particle anisotropy
- Distinct signature from Doppler beaming = energy-independent boosting
Energy-dependent synchrotron anisotropy

(Aitoff projection, $t = 397 \omega_c^{-1}$)

Solid angle containing 50% flux:

\[
\Omega_{50\%}/4\pi = 0.35
\]

\[
\Omega_{50\%}/4\pi = 0.18
\]

\[
\Omega_{50\%}/4\pi = 0.04
\]

Variability from narrow beams swinging past observer

(Cerutti+ 2013)
Expected lightcurves – (Crab model)

B. Cerutti & G. Werner

Predicted ultra-short time variability < 6 hours due to particle bunching and anisotropy (Cerutti+ 2013)

MODEL

Apr. 2011 flare

(Buehler+ 2012)

OBSERVATIONS

Observed ultra-short time variability < 8 hours

Observer

\[ \Omega_0/4\pi = 0.04 \]
SUMMARY...

- EM acceleration of relativistic jets can lead to conditions conducive to particle heating/acceleration
- Occurs at a moderate to high magnetization
  - Disfavors shock acceleration
  - Favors reconnection in discrete current sheets or turbulence
- Large PIC simulations reveal robust phenomenology
  - Power-law indices: similar dependence on for reconnection/turbulence in pair/electron-ion plasma
  - High energy cutoffs
  - Observed spectra consistent with ~ 1 (natural regulation?)
- Separate “linear accelerator” mechanism predicted by reconnection theory could explain hard -ray flares