Efficient acceleration of relativistic magneto-hydrodynamic jets: theoretical study

(Toma & Takahara 2013, Prog. Theor. Exp. Phys., 2013, 3E02)

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Relativistic Jets

- Active galactic nuclei, gamma-ray bursts, etc.
- Lorentz factor $\Gamma \sim 10^{1-10^{3}}$ (?)
- One of the major problems in astrophysics

- Those objects are candidates of high-energy CR, $\nu$, and GW emitters.
Promising Scenario

- Steady extraction of rotational energy of accretion disk or BH (Goldreich & Julian 1969; Blandford & Znajek 1977; see also KT & Takahara 2014) → Poynting-domin jet (Kino+ 15)
- Mass loading mechanism unknown. Unsteady process or diffusion of high-energy hadrons? (KT & Takahara 2012; Kimura et al. 2015)
- Matter acceleration by Lorentz force
- Collimation by external pressure

(see numerical simulations by J. McKinney, A. Tchekhovskoy, etc.)
Matter acceleration, collimation

- Particles are accelerated by $J \times B$ force (= energy flux conversion from Poynting to kinetic)
- $J \times B$ force also collimates the flow
- But $\rho E$ force expands the flow
- In the relativistic flow, $E \sim -v_p \times B_\phi \sim B_\phi$ beyond the light cylinder $\Rightarrow B_\phi^2$ stress is not effective for collimation (except for the region near the axis) (Komissarov+09; Lyubarsky 09)

- Efficient acceleration requires expansion of magnetic flux tube ($\sim$ de Laval nozzle) (e.g. Begelman+94; KT & Takahara 2013)
Acceleration mechanism

**De Laval nozzle:**
**one-dimensional hydrodynamic case**

\[
\left(1 - \frac{v^2}{c_s^2}\right) \frac{dv}{v} = \frac{-dS}{S}
\]

\(v < c_s\)  
\(\text{High } P\)  

\(v > c_s\)  
\(\text{Low } P\)

**Two-dimensional magneto-hydrodynamic case**

\[
\left(1 - \frac{u_f^2}{u_p^2}\right) \frac{d\Gamma}{\varepsilon - \Gamma} + \frac{c^2\Gamma_{in}}{r^2\Omega^2\Gamma} \frac{d\Gamma}{u_p} + \left(1 + \frac{2\Gamma_{in}}{\Gamma}\right) \left(-v_\phi dv_\phi\right) v_p^2 = \frac{-dS}{S}.
\]

Magnetic flux tube must be expanded when the super-fast flow is accelerated.
Acceleration mechanism

(Komissarov, Vlahakis, Konigl & Barkov 2009)

- Steady axisymmetric MHD solution
- BH gravity neglected
- External rigid wall (parabolic)
- Gradual acceleration
- Collimation near the axis leads to expansion of outer region

(see also Lyubarsky 2009; Asada, Nakamura et al. 2014)

Poloidal B field lines & Density

Poloidal currents & Lorentz factor
Acceleration efficiency

(Komissarov, Vlahakis, Konigl & Barkov 2009)

- Poynting/kinetic \( \sim 1 \) at \( r \sim 10^4 r_{lc} \)
  \((z \sim 10^6 r_{lc})\) which is extremely large distance
- But observations of blazars imply Poynting/kinetic \(< 0.1 \) at \( r \sim 10^3 r_{lc} \) (e.g. Kino+ 2002; Sikora + 2005)

- (Efficient magnetic dissipation?)

We look for boundary conditions for more efficient acceleration
Field line near the boundary

- Focus on the fluid motion along the field line near the boundary (not solving transverse structure)
- Assume the shape of the boundary
- Look for field structure for efficient acceleration
- External pressure

\[
\left. \left( \frac{B_p^2 + B_\varphi^2 - E^2}{8\pi} \right) \right|_{\psi=\psi_0} = P_{\text{ext}}(z).
\]
Examples of field line structure

- Boundary: $y = 0.1 \, x^2$
- Plot the field line of $\Psi = 0.95 \, \Psi_0$

\[
y = D \left( \frac{x}{d} \right)^{a(\psi)}, \quad y = A_0 x^{a_0} + F(\psi) x^b,
\]

More efficient acceleration
Solutions of cold MHD wind eq.

Both cases show Poynting/kinetic $\sim 0.3$ at $r \sim 3 \, r_{lc}$

More efficient acceleration, consistent with blazar observations
Solutions: external pressure

- **Type 1**: Dotted line
- **Type 2-A**: Dotted-dashed line
- **Type 2-B**: Dotted line
- **Type 2-C**: Dashed line

**Figure 7 (top right)** shows a wind solution for $\psi^5_0$ as that for Type 1, i.e., the dashed line in Fig. 6 (top right) represents the poloidal field line of $\psi_1^5$. This corresponds to Case 1. At $x \approx 18$, this is comparable to the observational suggestion of a conical shape. The field line of $\psi_1^5$ decreases as a power law function of $x$.

**Jet axis**

**Outflow region**

**External medium could be the corona with closed field loops?**

**Very rapid decay!**

**Longer rapid decay, more efficient acceleration**

**Equation (4.12)**

The range where $x < 1.5 \times 10^9$ is shown in Fig. 6 (bottom left). This means that $x > 10^9$.

**Equation (4.9)**

$\xi \propto x^{-12}$.

**Solution**

- **External pressure**
  - $P_{\text{ext}}$ is shown in Fig. 6 (top right). It drops very rapidly at $x < 10^5$. This is simply a generic property for the cases of Type 1.
  - For this parameter value, the rapid acceleration phase just beyond $x = B_0$ is comparable to the observational suggestion of a conical shape. The field line of $\psi_1^5$ decreases monotonically, as can be expected by Eq. (4.12).

**Equation (4.10)**

The parameters are $a = 10^5$, $b = 10^3$, and $c = 10^2$. This is shown in Fig. 6 (top right) and with the same range of $x$.

**Equation (4.13)**

$P_{\text{ext}}$ decreases as a power law function of $x$.

**Equation (4.14)**

Very rapidly at $x < 10^5$. This is simply a generic property for the cases of Type 1.

**Equation (4.15)**

$\xi \propto x^{-12}$.

**Equation (4.16)**

$\xi \propto x^{-12}$.
Summary

• MHD jet can accelerate the particles to relativistic speeds (e.g. Komissarov+ 2009) (consistent with radio observations of M87 jet... Asada+ 2014; Kino+ 2015)

• More efficient acceleration is needed for explaining the blazar gamma-ray spectra

• We show boundary conditions for very efficient acceleration, which correspond to very rapid decay of external pressure

• Another possibility is efficient magnetic dissipation (whose mechanism is not clear yet)