Simulations and Analytic Models of Magnetized Gamma-Ray Burst Jets: Beyond the Progenitor Star

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Tchekhovskoy et al. (2009, arXiv:0911.2228)
Gamma-ray bursts

Come in 2 flavors:

Short, \( \lesssim 2 \text{ s} \)

Coalescence of a compact object binary

Long, \( \gtrsim 2 \text{ s} \)

Death of a massive star (Woosley 1993)
Gamma-ray bursts (GRBs)

- **Acceleration**: ultra-relativistic velocity, Lorentz factor $\gamma \gtrsim 100$  
  - Non-relativistic prompt spectrum

- **Collimation**: opening angle $\theta \lesssim 0.1$

- **Relation between acceleration and collimation**: $\gamma \theta \gtrsim 20$
  - Jet breaks in afterglow emission

Recent simulations of magnetized (MHD) continuously collimated jets (Komissarov et al. 2009):

- $\gamma \theta \lesssim 1$

I will now present the first model of a magnetized GRB jet that correctly reproduces *both* collimation and acceleration.
How do magnetic jets work?

\[ p = \frac{B^2_\phi}{8\pi} \]

Field toroidally-dominated

\[ B_\phi \gg B_z \quad v_{\text{fluid}} = v_{\text{field}} \]
Simulation setup

Confined Jet

Central black hole

Wall

GRB jet quick facts:
1. Ultra-relativistic: $\gamma \gtrsim 100$
2. Collimated: $\theta = 0.04 - 0.2$
3. Product $\gamma \theta \simeq 20 \gg 1$

Numerical Approach

Time-dependent ultrarelativistic MHD equations
Axisymmetry, perfect conductivity, and zero T

Problem setup

Perfectly conducting spinning compact object

Collimating wall of shape $z \propto R^\alpha$

Model parameters

Jet wall shape
Spin of compact object
Magnetic field strength
Surface mass loss rate
Why is $\gamma \theta \lesssim 1$ in confined jets?

- Communication is essential
- Jet boundary B needs to keep announcing its trajectory to the rest of the jet to avoid collisions
- All signals travel inside Mach cone $\xi$:
  \[
  \theta < \xi \approx \frac{1}{\gamma}
  \]
- Communication across jet $\rightarrow \theta < \xi$
- Robust conclusion: $\gamma \theta \lesssim 1$ in confined jets

GRB jet quick facts:
1. Ultra-relativistic: $\gamma \gtrsim 100$
2. Collimated: $\theta = 0.04 - 0.2$
3. Product $\gamma \theta \approx 10 \gg 1$
Simulation setup

Confined Jet

$\gamma \theta = 2 \times$

Deconfined Jet

$\gamma \theta = 20 \checkmark$
Simulation setup

Numerically-challenging problem

High magnetization and Lorentz factor (∼ 1000): very stiff regime

Evolution over 10 orders of magnitude in distance

Our numerical method uses

Collimating grid that follows field lines at high resolution 1536x256

Equivalent resolution using non-collimating grid: 1536x100,000

Evolve only non-stationary region to speed up computation
Confined vs. Deconfined

GRB jet quick facts:
1. Ultra-relativistic: $\gamma \gtrsim 100$
2. Collimated: $\theta = 0.04 - 0.2$
3. Product $\gamma \theta \approx 20 \gg 1$

MHD models can produce jet breaks
Understand this analytically

After jet loses ambient pressure support, it switches from the **fully confined** solution to the **fully unconfined** solution (AT+ 2009).

**GRB jet quick facts:**
1. Ultra-relativistic: \( \gamma \gtrsim 100 \)
2. Collimated: \( \theta = 0.04 - 0.2 \)
3. Product \( \gamma \theta \approx 20 \gg 1 \)

\[ \gamma = 500 \]
\[ \theta = 0.04 \]
\[ \gamma \theta = 20 \]
Understand this analytically (2/3)

Fully unconfined jet:
\[ \gamma_3 \propto \log^{1/3} r \]  
(Tomimatsu 94)

Fully confined jet, large distance. Centrifugal force slows jet down (AT+ 2008):
\[ \gamma_2 \approx \left( \frac{3R_c}{R} \right)^{1/2} \]

Fully confined jet, short distance. Linear increase:
\[ \gamma_1 \approx \Omega R \]  
(Michel 1969)
Centrifugal force slows jet down (approximate)

\[ F_m = -\nabla p_m = \frac{\epsilon_m}{R} \]

\[ F_c = \frac{\epsilon_m \gamma^2}{R_c} \]

\[ \frac{\epsilon_m}{R} = \frac{\epsilon_m \gamma^2}{R_c} \]

\[ \gamma = \left( \frac{R_c}{R} \right)^{1/2} \]
Required ingredients for GRB jets

Both propagation inside and outside the star are required for GRB jets:

1) Fully confined jets are too slow for their opening angles: $\gamma \theta \lesssim 1$

2) Fully deconfined jets have too large opening angles

Bottom line: need both

1) confinement to collimate the jet initially and
2) deconfinement to accelerate the jet
Conclusions

- **Numerical & analytical** models of magnetized *deconfined* ultra-relativistic jets, extending over 10 orders of magnitude in distance well into the afterglow region.

- Just outside the star, our jets undergo an *abrupt period of acceleration* during which $\gamma$ increases but $\theta$ is constant.

- *Deconfinement* is necessary to achieve ultrarelativistic $\gamma$ and $\gamma \theta \gg 1$ required by jet breaks observations.

- **Confined** jets with subequipartition magnetic fields always have $\gamma \theta \lesssim 1$.

- Future work is the self-consistent simulation of magnetized jet propagation through realistic stellar envelope out to the afterglow region.