Magnetic Acceleration, Collimation, and Clues on Composition of Gamma-ray Burst Outflows

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Magnificent Jets

M87 galaxy
(radio, 20 cm)

Centaurus A galaxy
(radio/optical/X-ray)

10⁹ solar mass black hole
4000 light years

10⁸ solar mass black hole
13000 light years

1 light year
1000 black hole radii
Superluminal Motion in Jets: Different Masses, Similar Speeds

Active Galaxy M87 with $M_{BH} = 3 \times 10^9 M_{\odot}$:

X-ray Binary GRS 1915+105 with $M_{BH} = 15 M_{\odot}$:

Relativistic jet from a supermassive BH

Relativistic jet from a stellar-mass BH
Gamma-ray bursts (GRBs)

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

- **Weak mag. field**: $\Gamma_m \epsilon_m / \rho c^2 \equiv \sigma \lesssim 1$

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

- **Relation between acceleration and collimation**: $\gamma \theta \gtrsim 10$

- Recent simulations of magnetized (MHD) continuously collimated jets (Komissarov et al. 2009):
  - $\gamma \theta \lesssim 2$

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Tchekhovskoy, Narayan, & McKinney 2010, New Astronomy, 15, 749
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- **Prompt emission**

- Recent simulations of magnetized (MHD) continuously collimated jets (Komissarov et al. 2009):
  - $\gamma \theta \lesssim 2$

- Spinning black hole or NS

- Magnetized Jet

- Star

- Jet breaks in afterglow emission

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How do magnetic jets work?

Field toroidally-dominated
\[ B_\phi \gg B_z \]

\[ p = \frac{B_\phi^2}{(8\pi)} \]
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Field toroidally-dominated

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How do magnetic jets work?

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

\[ \sigma = \frac{\Gamma m \epsilon_m}{\rho c^2} \]
GRB Jets: Problem Setup

Simulations of magnetized confined jets:
\[ \gamma \theta \lesssim 2 \]
(Komissarov et al., MNRAS, 2009)

GRB jets are DEconfined:
\[ \gamma \theta \geq 10 \]

Confined
\[ \gamma \theta = 2 \]

Deconfined
\[ \gamma \theta = 20 \]
Deconfinement Acceleration

\[ \gamma \gtrsim 100 \]
\[ \theta \lesssim 0.1 \]
\[ \gamma \theta \gtrsim 10 \]
\[ \sigma \lesssim 1 \]

\[ \gamma = 100 \quad \theta = 0.02 \quad \gamma \theta = 2 \]
\[ \gamma = 500 \quad \theta = 0.04 \quad \gamma \theta = 20 \]
Understanding Deconfinement

After jets lose ambient pressure support, they switch from the fully confined solution to the fully unconfined solution.
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$\gamma$ increases by 5x and $\theta$ by 2x. So, $\gamma\theta$ rises from 2 to 20 (AT+ 2010)

$GRB$: $\gamma \gtrsim 100$ ✓
$\theta \lesssim 0.1$ ✓
$\gamma\theta \gtrsim 10$ ✓
$\sigma \lesssim 1$

$\sigma = \Gamma_m \epsilon_m / \rho c^2$

$\gamma = 500$
$\theta = 0.04$
$\gamma\theta = 20$
Understanding Deconfinement

After jets lose ambient pressure support, they switch from the **fully confined** solution to the **fully unconfined** solution.

- $\gamma$ increases by 5x and $\theta$ by 2x. So, $\gamma\theta$ rises from 2 to 20 (AT+ 2010)

- Numerical deconfined jet
- Analytic fully unconfined jet (AT+ 2009)
- Analytic fully confined jet (AT+ 2008)
- Stellar surface
Understanding Deconfinement

After jets lose ambient pressure support, they switch from the fully confined solution to the fully unconfined solution.

\( \gamma \) increases by 5x and \( \theta \) by 2x. So, \( \gamma \theta \) rises from 2 to 20 (AT+ 2010)

\[ \sigma = \frac{\Gamma_m \epsilon_m}{\rho c^2} \]

\[ \begin{align*} 
\gamma &= 500 \\
\theta &= 0.04 \\
\gamma \theta &= 20 \\
\sigma &= 1 
\end{align*} \]
Jet Acceleration and Collimation

- Relation between jet acceleration and collimation
  \[ \gamma \theta \sim C \sigma^{1/2} \]  
  (AT, Narayan, McKinney 2010)

  Confined jets: \( C \lesssim 1 \)
  Deconfined jets: \( C \approx 20 \)

- Faster jets are more collimated

- For our fiducial model, \( \mu = 1000, \theta = 0.04 \), which gives \( \gamma \approx 600 \).
  The flow reaches magnetic field equipartition, just as in the simulation.

- But this does not always happen!

- Highly initially magnetized jets remain highly magnetized: jet with \( \mu = 10^6, \theta = 0.04 \) ends up at \( \gamma \approx 6 \times 10^3 \).
Jet Composition

- Relation between jet acceleration and collimation
  \[ \gamma \theta \sim C \sigma^{1/2} \]
  (AT, Narayan, McKinney 2010)

  Confined jets: \( C \lesssim 1 \)
  Deconfined jets: \( C \approx 20 \)

- What do observations tell us?
  - Most GRBs: \( \gamma \theta \sim 10 - 30 \) \( \rightarrow \) \( \sigma \sim 1 \)
    - subdominant magnetic fields, consistent with standard GRB emission models
  - Some GRBs: \( \gamma \theta \sim 100 \) \( \rightarrow \) \( \sigma \sim 25 \gg 1 \)
    - dynamically-important magnetic fields, new physics needed?

If many more GRBs show \( \gamma \theta \sim 100 \), this will challenge standard GRB emission models that require \( \sigma \lesssim 1 \).