Magnetic acceleration
of GRB Jets

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The 1st Capitol Chat, on “GRBs and their prompt emission radiation mechanism”, June 9, 2015, GWU, Washington DC, USA
Ideal MHD acceleration: numerical + analytic results (Komissarov 09; Lyubarsky 09; Tchekhovskoy 10)

- **Unconfined** flows rapidly lose lateral causal contact, become radial & stop accelerating when $\Gamma_\infty \sim \sigma_0^{1/3}$ & $\sigma_\infty \sim \sigma_0^{2/3} \gg 1$ (Goldreich & Julian 1970; Tomimatsu 1994; Beskin et al. 1998)

- **Weak confinement**: $p_{\text{ext}} \propto z^{-\alpha}$ with $\alpha > 2 \Rightarrow$ lose lateral C.C. become conical & stop accelerating later; **causal contact loss**: $\Gamma_\infty \sim \sigma_0^{1/3}\theta_{\text{jet}}^{-2/3}$, $\sigma_\infty \sim (\sigma_0\theta_{\text{jet}})^{2/3}$, efficient conversion: $\Gamma_\infty \theta_{\text{jet}} < 1$

- **Strong confinement**: $p_{\text{ext}} \propto z^{-\alpha}$ with $\alpha < 2 \Rightarrow$ stay in causal contact $\Gamma \propto z^{\alpha/4}$ and reach $\Gamma_\infty \sim \sigma_0$, $\sigma_\infty \sim 1$, $\Gamma_\infty \theta_{\text{jet}} \leq 1$

- Hydromagnetic launching naturally helps avoid high baryon loading that limits the maximal possible asymptotic L.F.

- Acceleration of steady, relativistic supersonic flows:
  
  **Thermal**: fast, robust, efficient
  
  **Magnetic**: slow, delicate, less efficient
The “σ-problem”: for a “standard” steady ideal MHD axisymmetric flow

- \( \Gamma_\infty \sim \sigma_0^{1/3} \) & \( \sigma_\infty \sim \sigma_0^{2/3} \gg 1 \) for a spherical flow; \( \sigma_0 = B_0^2/4\pi \rho_0 c^2 \)
- In PWN the solution is dissipation of the striped wind
- However, this doesn’t work in relativistic jet sources

- Jet collimation helps, but not enough: \( \Gamma_\infty \sim \sigma_0^{1/3} \theta_{jet}^{-2/3} \)
  \( \sigma_\infty \sim (\sigma_0 \theta_{jet})^{2/3} \) & \( \Gamma \theta_{jet} \leq \sigma^{1/2} \) (~1 for \( \Gamma_\infty \sim \Gamma_{max} \sim \sigma_0 \))
- Still \( \sigma_\infty \geq 1 \Rightarrow \) inefficient internal shocks, \( \Gamma_\infty \theta_{jet} \gg 1 \) in GRBs
- Sudden drop in external pressure can give \( \Gamma_\infty \theta_{jet} \gg 1 \) but still \( \sigma_\infty \geq 1 \) (Tchekhovskoy et al. 2009) \( \Rightarrow \) inefficient internal shocks
Alternatives to the “standard” model

- **Axisymmetry**: non-axisymmetric instabilities (e.g. the current-driven kink instability) can tangle-up the magnetic field (Heinz & Begelman 2000)

  - If $\langle B_r^2 \rangle = \alpha \langle B_\phi^2 \rangle = \beta \langle B_z^2 \rangle$; $\alpha, \beta = \text{const}$ then the magnetic field behaves as an ultra-relativistic gas: $p_{\text{mag}} \propto V^{-4/3}$

  - \( \Rightarrow \) magnetic acceleration as efficient as thermal

- **Ideal MHD**: a tangled magnetic field can reconnect (Drenkham & Spruit 2002; Lyubarsky 2010 - Kruskal-Schwarzschild instability (like R-T) in a “striped wind”) magnetic energy \( \rightarrow \) heat (+radiation) \( \rightarrow \) kinetic energy

- **Steady-state**: effects of strong time dependence (JG, Komissarov & Spitkovsky 2011; JG 2012a, 2012b)
Impulsive Magnetic Acceleration: $\Gamma \propto R^{1/3}$

Useful case study:

Initial value of magnetization parameter:

$$\sigma_0 = \frac{B_0^2}{4\pi\rho_0 c^2} \gg 1$$

1. $\langle \Gamma \rangle_E \approx \sigma_0^{1/3}$ by $R_0 \sim \Delta_0$
2. $\langle \Gamma \rangle_E \propto R^{1/3}$ between $R_0 \sim \Delta_0$ & $R_c \sim \sigma_0^2 R_0$ and then $\langle \Gamma \rangle_E \approx \sigma_0$
3. At $R > R_c$ the sell spreads as $\Delta \propto R$ & $\sigma \sim R_c/R$ rapidly drops

- Complete conversion of magnetic to kinetic energy!
- This allows efficient dissipation by shocks at large radii

$\Delta$ is a vacuum "wall"

$\sigma_0 = B_0^2 / 4\pi\rho_0 c^2 > 1$

$t_0 \approx R_0/c$
$t_c \approx R_c/c$

Complete conversion of magnetic to kinetic energy!

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1st Steady then Impulsive Acceleration

- Our test case problem has no central engine: it may be, e.g., directly applicable for giant flares in SGRs; however:
- In most astrophysical relativistic (jet) sources (GRBs, AGN, μ-quasars) the variability timescale \( t_v \approx R_0/c \) is long enough \( (> R_{ms}/c) \) that steady acceleration operates & saturates (at \( R_s \))
- Then the impulsive acceleration kicks in & leads to \( \sigma < 1 \)

\[
\theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{2/9} R_{lc} \quad \theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{4/9} R_{ms} \quad \theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{2/3} R_s \quad \theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{4/3} R_0 \quad \theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{4/9} R_{cr,h} \quad \theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{2/3} R_{cr,t} \quad \theta_j \approx \left( \frac{\sigma_0 \theta_j}{\sigma_0} \right)^{2/9} R_c
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