Magnetic acceleration of GRB Jets

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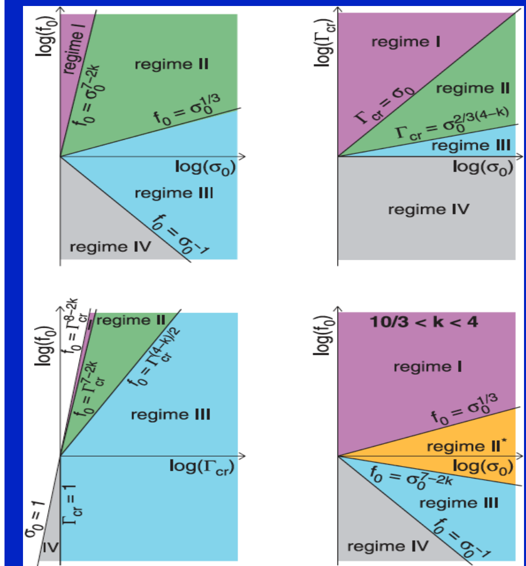
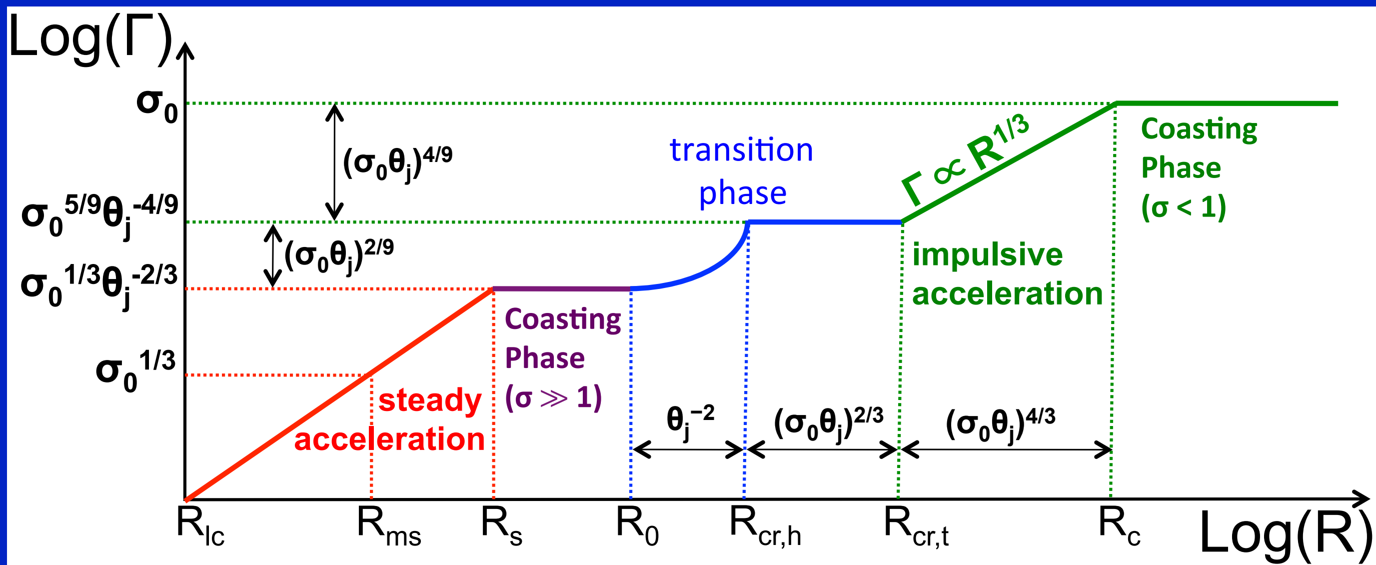




The 1st Capitol Chat, on "GRBs and their prompt emission radiation mechanism", June 9, 2015, GWU, Washington DC, USA

Ideal MHD acceleration: numerical + analytic results (Komissarov+ 09; Lyubarsky 09; Tchekhovskoy+10)

- **Unconfined** flows rapidly lose lateral causal contact, become radial & stop accelerating when $\boldsymbol{\Gamma_\infty \sim \sigma_0^{1/3}}$ & $\boldsymbol{\sigma_\infty \sim \sigma_0^{2/3} \gg 1}$ (Goldreich & Julian 1970; Tomimatsu 1994; Beskin et al. 1998)
- **Weak confinement**: $\boldsymbol{p_{ext} \propto z^{-\alpha}}$ with $\boldsymbol{\alpha > 2 \Rightarrow}$ lose lateral C.C. become conical & stop accelerating later; **causal contact loss:** $\Gamma_\infty \sim \sigma_0^{1/3}\theta_{jet}^{-2/3}$, $\sigma_\infty \sim (\sigma_0\theta_{jet})^{2/3}$, efficient conversion: $\Gamma_\infty\theta_{jet} < 1$
- **Strong confinement**: $\boldsymbol{p_{ext} \propto z^{-\alpha}}$ with $\boldsymbol{\alpha < 2 \Rightarrow}$ stay in causal contact $\Gamma \propto z^{\alpha/4}$ and reach $\Gamma_\infty \sim \sigma_0$, $\sigma_\infty \sim 1$, $\Gamma_\infty\theta_{jet} \leq 1$
- Hydromagnetic launching naturally helps avoid high baryon loading that limits the maximal possible asymptotic L.F. Γ_∞
- 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: $\Gamma_\infty \sim \sigma_0^{1/3}\theta_{jet}^{-2/3}$, $\sigma_\infty \sim (\sigma_0\theta_{jet})^{2/3}$ & $\Gamma\theta_{jet} \lesssim \sigma^{1/2}$ (~1 for $\Gamma_\infty \sim \Gamma_{max} \sim \sigma_0$)
- Still $\sigma_\infty \gtrsim 1$ ⇒ 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 $\sigma_\infty \gtrsim 1$ (Tchekhovskoy et al. 2009) ⇒ inefficient internal shocks

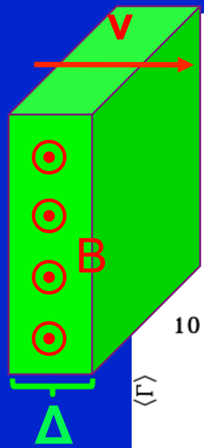
Alternatives to the "standard" model

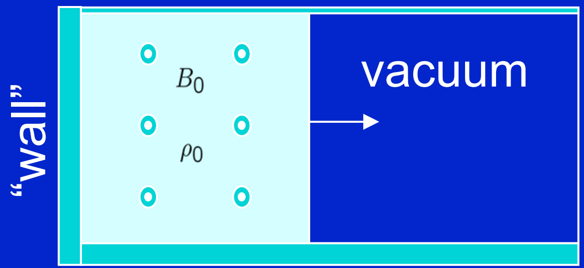
- ~~Axisymmetry~~: non-axisymmetric instabilities (e.g. the current-driven kink instability) can tangle-up the magnetic field (Heinz & Begelman 2000)
  - If $\langle B_r^2 \rangle = \alpha \langle B_\phi^2 \rangle = \beta \langle B_z^2 \rangle \;;\;\; \alpha, \beta = \text{const}$ then the magnetic field 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)

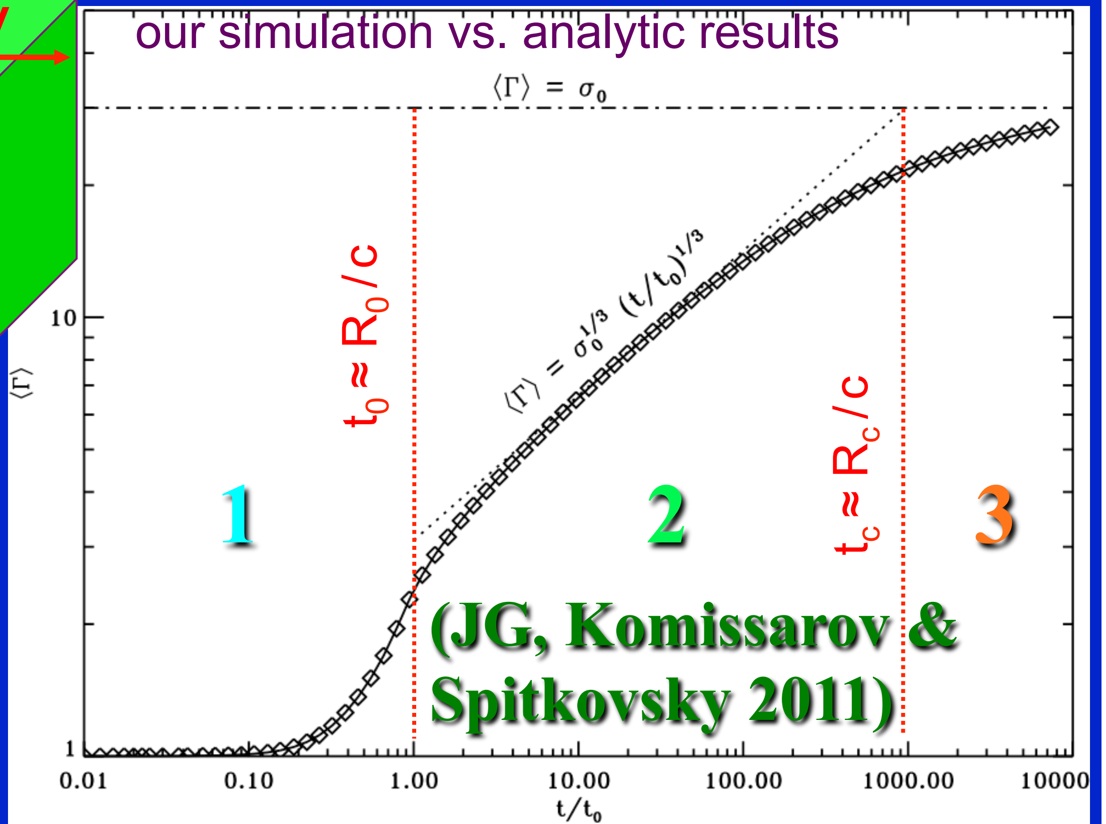
Impulsive Magnetic Acceleration: $\Gamma \propto R^{1/3}$

Useful **case study**:

Initial value of magnetization parameter: $\sigma_0 = \dfrac{B_0^2}{4\pi\rho_0 c^2} >> 1$







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**

1^{st} 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 $\sigma < 1$