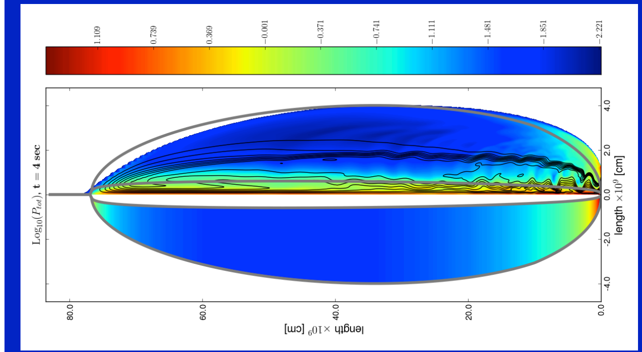
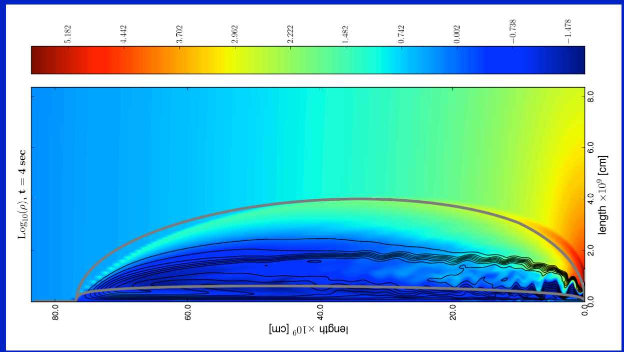
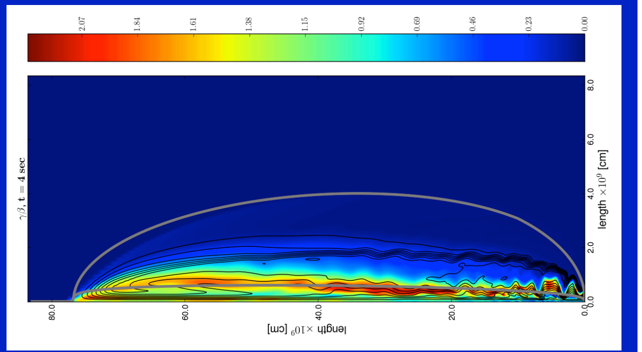
Jet in star: jet composition in the collapsar model & GRB duration distribution

Jonathan Granot

Open University of Israel





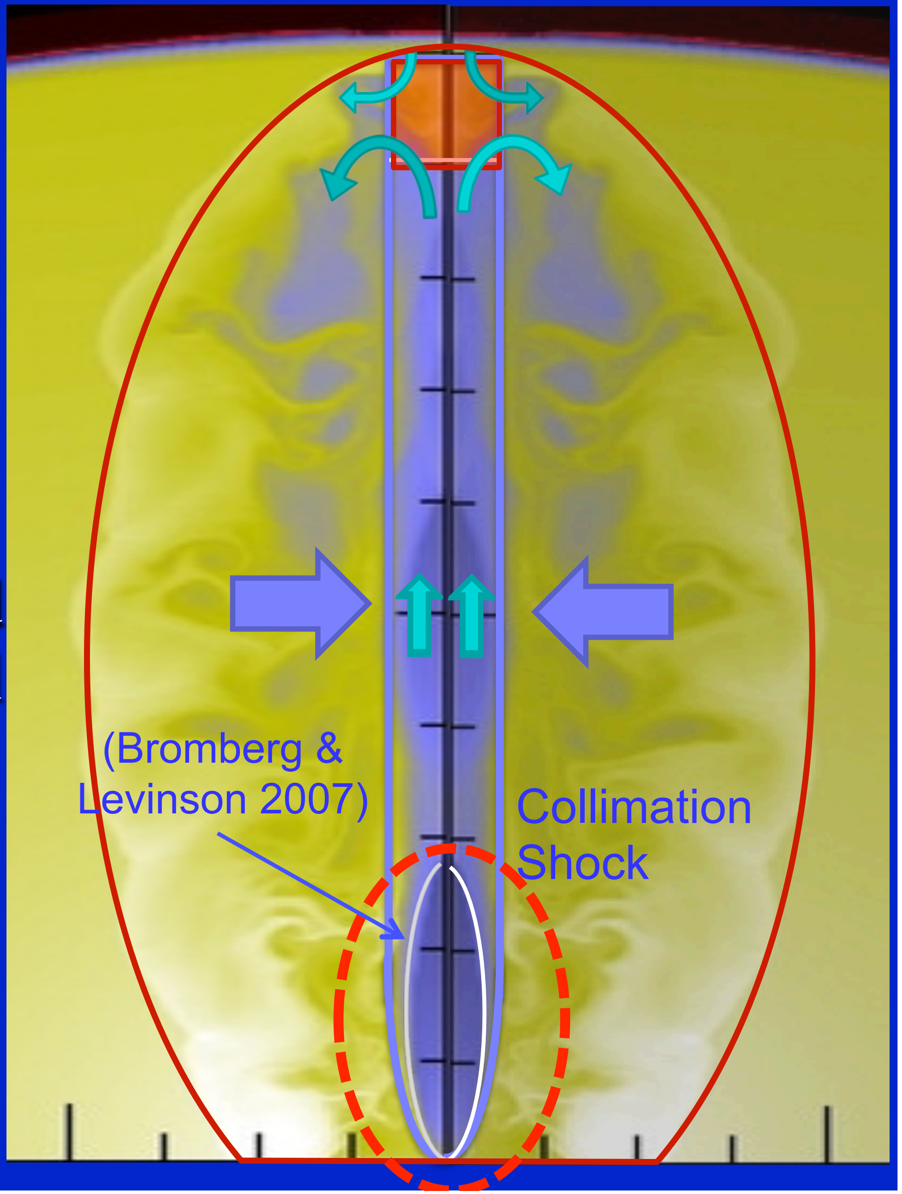


The 1st Capitol Chat, on "GRBs and their prompt emission radiation mechanism", June 8, 2015, GWU, Washington DC, USA

Hydrodynamic GRB Jet in its parent star

- The Jet develops a slow-moving 'head', were there is a pressure balance between the shocked jet material & external medium
- At the head jet matter decelerates by a reverse shock, flows sideways & forms a high-pressure cocoon that collimates the jet
- To propagate the head must be fed by jet material & the jet would fail if engine stops before $z_h \cong R(1-\beta)$
- Breakout time (Bromberg et al. 2011)

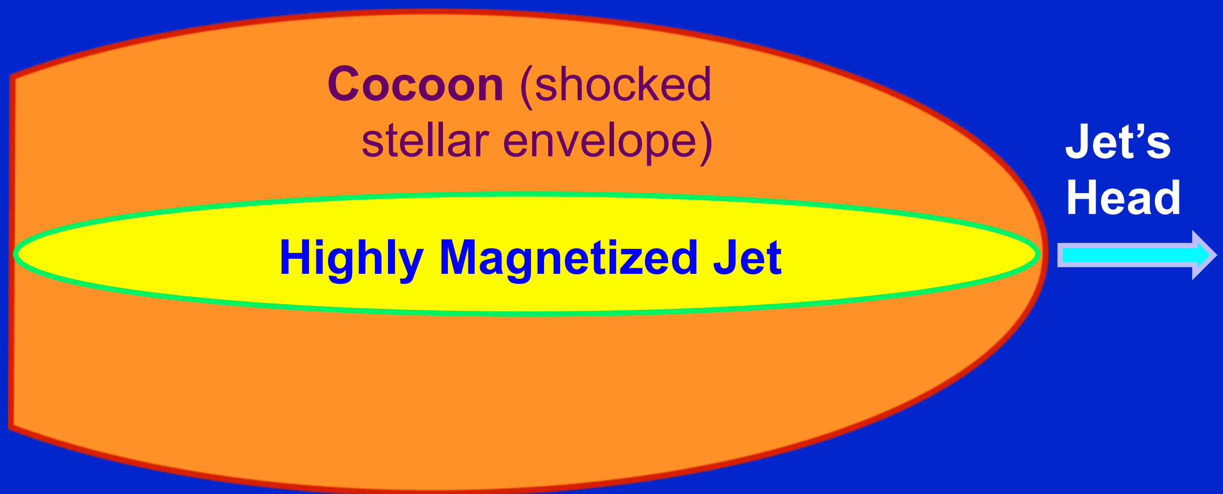
$$t_b \cong 15\,\mathrm{sec}\left(\frac{L_{\mathrm{iso}}}{10^{51}\,\mathrm{erg/s}}\right)^{-1/3}\left(\frac{\theta_0}{10^\circ}\right)^{2/3}\left(\frac{R}{5R_\odot}\right)^{2/3}\left(\frac{M}{15M_\odot}\right)^{1/3}$$



GRB Jet propagation in its parent star: highly magnetized vs. hydrodynamic jets

- The flow must decelerate to match it's head velocity, but for high-σ a shock can't do it ⇒ the jet converges near its head
- Narrower head ⇒ larger head velocity ⇒ faster jet breakout
- Relativistic head ⇒ less energy into cocoon & supernova
- The head velocity is independent of the detailed jet structure ⇒ simplifies the model & allows (semi-) analytic solutions

(Bromberg, JG, Lyubarsky & Piran 2014)



GRB Jet propagation in its parent star: highly magnetized vs. hydrodynamic jets

- The flow must decelerate to match it's head velocity, but for high-σ a shock can't do it ⇒ the jet converges near its head
- Narrower head ⇒ larger head velocity ⇒ faster jet breakout
- Relativistic head ⇒ less energy into cocoon & supernova
- The head velocity is independent of the detailed jet structure ⇒ simplifies the model & allows (semi-) analytic solutions

$$t_b \cong \left(\frac{R}{\beta c}\right)(1-\beta) \cong \frac{R}{2\Gamma_h^2 c}$$

$$t_b \cong 1.8\,\mathrm{sec}\left(\frac{L_{\rm iso}}{10^{51}\,\mathrm{erg/s}}\right)^{-1/3}\left(\frac{r_{\rm L}}{5\times10^{7}\,\mathrm{cm}}\right)^{2/3}\left(\frac{M}{15M_\odot}\right)^{1/3}$$

- Levinson & Begelman (2013): current-driven instabilities dissipate most of the magnetic field → a hydrodynamic jet
- This is still unclear & strongly affects the jet dynamics

Jet breakout time from its parent star:

$$t_\gamma = t_e - t_b$$

Prompt GRB duration → t_γ; Engine activity time → t_e; Jet breakout time → t_b

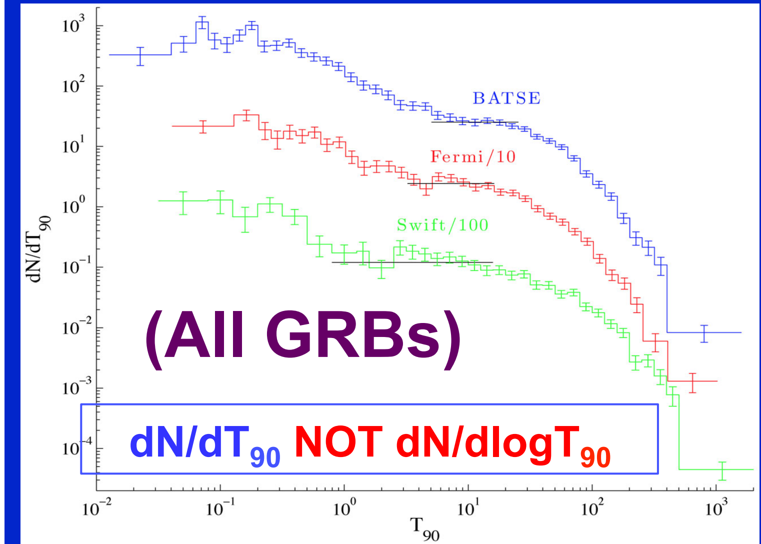
- Outflow from the central source that reaches the jet's head while it is in the star deposits its energy there: helps the jet bore its way out $t < t_b$
- Only outflow that doesn't reach the jet's head inside the star can contribute to powering the GRB prompt emission: $t > t_b$
- $t_e > t_b \Rightarrow$ normal GRB; $t_e < t_b \Rightarrow$ a failed (low-luminosity?) GRB
- The resulting prompt GRB duration distribution has two limits:

$$p_\gamma(t_\gamma) = p_e(t_e = t_\gamma + t_b) \approx \begin{cases} p_e(t_b) & t_\gamma << t_b \\ p_e(t_\gamma) & t_\gamma >> t_b \end{cases}$$

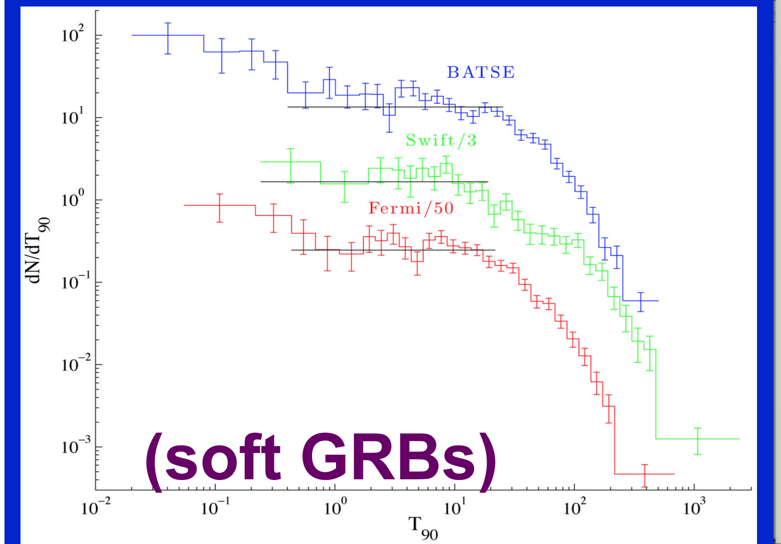
a constant value ($t_\gamma << t_b$)

reflects the engine duration distribution ($t_\gamma >> t_b$)

The GRB Duration Distribution:

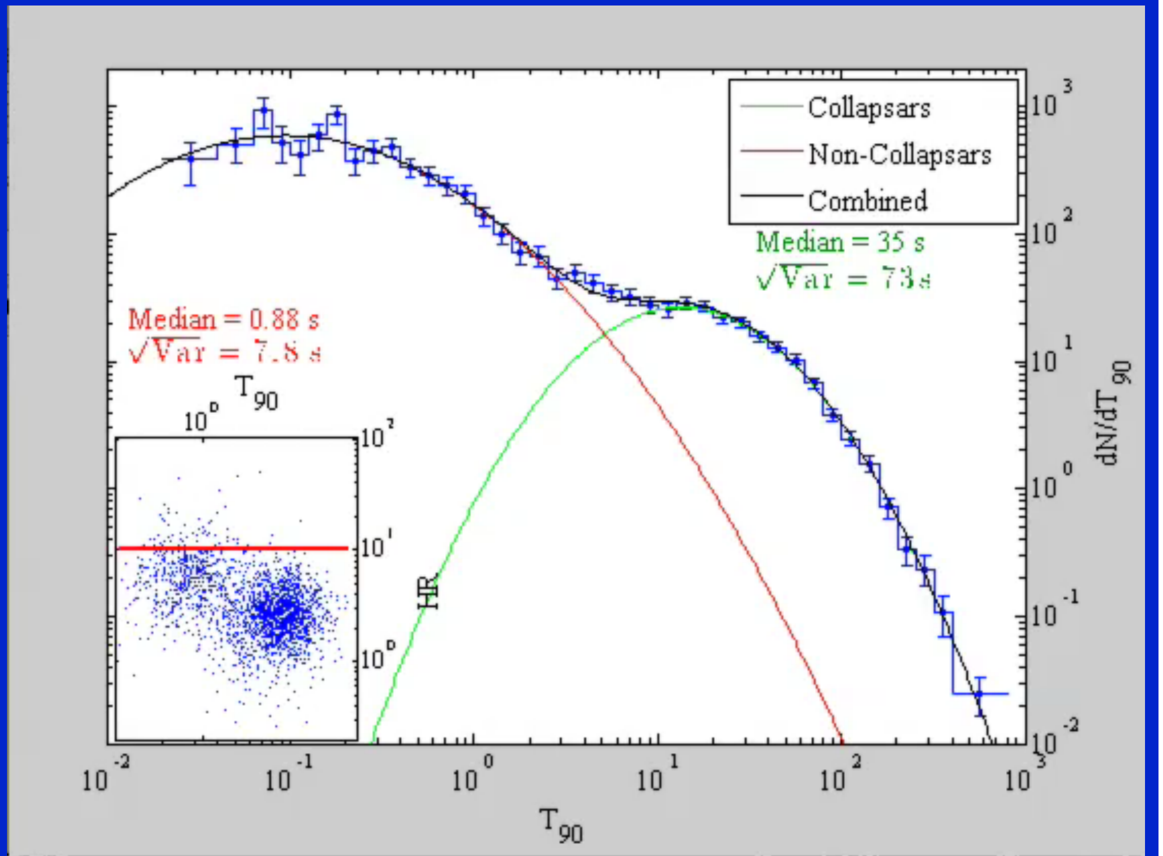


(Bromberg, JG & Piran 2015)



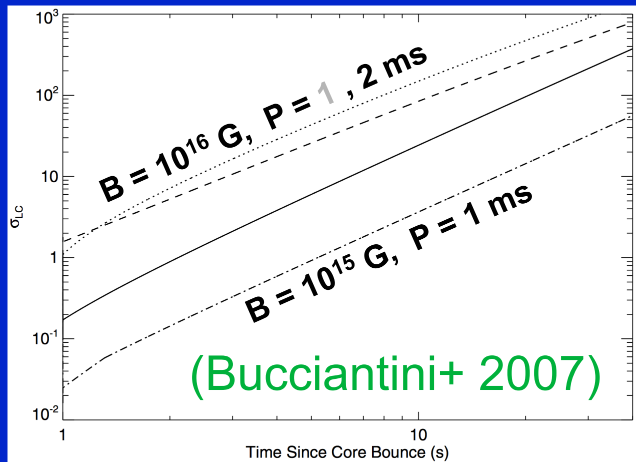
- The plateau is larger & clearer for soft GRBs – without most short GRBs
- Observed plateaus reach up to ~20-30 s

$\Rightarrow$ turnover at to ~40-50 s $\Rightarrow$ t_b ~10-15 s



Implications & Conclusions:

- The observed GRB duration distribution suggests $t_b \sim 10\text{-}15\,\mathrm{s}$ $\Rightarrow$ favor a hydrodynamic over magnetic jet before breakout
- Non-magnetic jet launching? maybe but $\nu\bar{\nu} \to e^+e^-$ $\Rightarrow$ $\dot{M}_{\rm acc} \geq 0.1\, M_\odot/\mathrm{s}$
- Hydromagnetic jet launching is most likely but the jet must somehow disrupt and dissipate most of its magnetic energy (become hydrodynamic) deep in the star (not via kink inst.)
- The initial jet magnetization σ_0 can increase over its lifetime
  - Occurs naturally in millisecond magnetar after its formation (Metzger+ 2007, 2011)



  - Can also occur in BH for high accretion rates (Kawanaka+ 2013).