The Proto-Magnetar Model for Gamma-Ray Bursts

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Metzger, Giannios, Thompson, Quataert & Bucciantini (in prep)
GRB 2010 Annapolis, November 2, 2010
Constraints on the Central Engine

- Energies - $E_\gamma \sim 10^{49-52}$ ergs
- Rapid Variability (down to ms)
- Duration - $T_\gamma \sim 10-100$ seconds
- Steep Decay after GRB
- Ultra-Relativistic, Collimated Outflow with $\Gamma \sim 100-1000$
- Association with Energetic Core Collapse Supernovae
- Late-Time Central Engine Activity (Plateau & Flaring)

BH versus NS
"Delayed" SN Explosion

Accretion vs. Neutrino heating

From A. MacFadyen
The Fates of Massive Stars (Heger et al. 2003)

Assumes neutrino-powered supernova with energy $\sim 10^{51}$ ergs!
The Collapsar “Failed Supernova” Model (Woosley 93)

- Energy - Accretion / Black Hole Spin
- Duration - Stellar Envelope In-Fall
- Hyper-Energetic SNe - Delayed Black Hole Formation or Accretion Disk Winds
- Late-Time Activity - Fall-Back Accretion

(e.g. MacFadyen & Woosley 1999; Aloy et al. 2000; MacFadyen et al. 2001; Proga & Begelman 2003; Takiwaki et al. 2008; Barkov & Komissarov 2008; Nagataki et al. 2007; Lindler et al. 2010)
Core Collapse with Magnetic Fields & Rotation
(e.g. LeBlanc & Wilson 1970; Bisnovatyi-Kogan 1971; Akiyama et al. 2003)

THE PROTO-NEUTRON STAR PHASE OF THE COLLAPSAR MODEL AND THE ROUTE TO LONG-SOFT GAMMA-RAY BURSTS AND HYPERNOVAE
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Collapsar Requirements:

- Angular Momentum
- Strong, Ordered Magnetic Field
  (e.g. Proga & Begelman 2003; McKinney 2006)
Millisecond Magnetar Model (Usov 92; Thompson 94)

\[ E_{\text{Rot}} \approx 3 \times 10^{52} \left( \frac{P}{1 \text{ ms}} \right)^{-2} \text{ ergs} \]

\[ E \approx 10^{49} \left( \frac{P}{1 \text{ ms}} \right)^{-4} \left( \frac{B_{\text{Dip}}}{10^{15} \text{ G}} \right)^2 \text{ ergs s}^{-1} \]

- Rapid Rotation \iff Efficient \( \alpha \)-\( \Omega \) Dynamo \iff Strong B-Field at \( P \sim 1 \text{ ms} \)
  (Duncan & Thompson 1992; Thompson & Duncan 1993)
Millisecond Magnetar Model (Usov 92; Thompson 94)

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- Rapid Rotation ⇔ Efficient \( \alpha-\Omega \) Dynamo ⇔ Strong B-Field at \( P \sim 1 \text{ ms} \) (Duncan & Thompson 1992; Thompson & Duncan 1993)

Galactic Magnetars exist…
SGR1806-20 Giant \( \gamma \)-Ray Flare in December 2004

…and can have massive progenitors

Westerlund I: O7 Stars still present!
Neutrinos Heat Proto-NS Atmosphere (e.g. $\nu_e + n \Rightarrow p + e^-$) $
\Rightarrow$ Drives Thermal Wind Behind SN Shock (e.g. Qian & Woosley 96)

Key Insight :
(Thompson, Chang & Quataert 04)

Neutron Stars are Born **Hot**, 
**Cool** via $\nu$-Emission: 
~$10^{53}$ ergs in $\tau_{KH} \sim 10$-100 s

Neutrino-Heated Wind

Before SN Explosion

After SN Explosion

Burrows, Hayes, & Fryxell 95
Effects of Strong Magnetic Fields & Rapid Rotation
(Thompson et al. 2004; Metzger et al. 2007,08)

"Helmet - Streamer"

**Outflow Co-Rotates with Neutron Star while**

\[
\frac{B^2}{8\pi} > \frac{1}{2}\rho v_r^2
\]

\[\Rightarrow\] Magneto-Centrifugal Acceleration

"Beads on a Wire"

\[\Rightarrow\] Enhanced Wind Power, Speed, & Mass Loss Rate

\[\Rightarrow\] From `Thermally-Driven’ to `Magnetically-Driven’ Outflow
Evolutionary Wind Models (BDM et al. 2010, in prep)

3D Magnetosphere Geometry
(e.g. Bucciantini et al. 2006; Spitkovsky 2006)

Calculate:

\[ \dot{E}(t), \dot{M}(t), \sigma(t) \sim \frac{\dot{E}}{\dot{M}c^2} = \Gamma_{\max}(t) \]

In terms of

Initial Rotation Period \( P_0 \), Dipole Field Strength \( B_{dip} \) & Obliquity \( \theta_{dip} \)
\[ \sigma \sim \Gamma_{max} = \frac{\dot{E}}{\dot{M}c^2} \propto \frac{B^2 \Omega^4}{L_\nu^{5/3}T^{10/3}} \]
Assume Successful Supernova (35 M☉ ZAMS Progenitor; Woosley & Heger 06)

- Magnetar with $B_{\text{dip}} = 3 \times 10^{15} \text{G}$, $P_0 = 1 \text{ ms}$

Average jet power and mass-loading match those injected by central magnetar
Wind becomes relativistic at $t \sim 2$ seconds;
Jet breaks out of star at $t_{bo} \sim R_{*}/\beta c \sim 10$ seconds
High Energy Emission (GRB) from \( t \approx 10 \) to \( \approx 100 \) s as Magnetization Increases from \( \sigma_0 \sim \Gamma \sim 30 \) to \( \sim 10^3 \)
1. **What** is jet’s composition? (kinetic or magnetic?)

2. **Where** is dissipation occurring? (photosphere? deceleration radius?)

3. **How** is radiation generated? (synchrotron, IC, hadronic?)
1. **What** is jet’s composition? (kinetic or magnetic?)

2. **Where** is dissipation occurring? (photosphere? deceleration radius?)

3. **How** is radiation generated? (synchrotron, IC, hadronic?)
Prompt Emission from Magnetic Dissipation
(e.g. Spruit et al. 2001; Drenkahn & Spruit 2002; Giannios & Spruit 2006)

Non-Axisymmetries $\Rightarrow$
Small-Scale Field Reversals
(e.g. striped wind with $R_L \sim 10^7$ cm)
$\Rightarrow$ Reconnection at speed $v_r \sim \varepsilon c$
$\Rightarrow$ Bulk Acceleration $\Gamma \propto r^{1/3}$
& Electron Heating

e.g. Coroniti 1990
Hot Electrons ⇒ IC Scattering (γ-rays) and Synchrotron (optical)
1. What is jet’s composition? (kinetic or magnetic?)
2. Where is dissipation occurring? (photosphere? deceleration radius?)
3. How is radiation generated? (synchrotron, IC, hadronic?)
Emission from Internal Shocks

Monotonically Increasing $\sigma_0 \sim \Gamma$
For fixed `microphysical parameters’ (e.g. $\varepsilon_e$ and $\varepsilon_B$), the Internal Shocks model predicts $E_{\text{peak}}$ increases during the GRB.
High Energy Emission (GRB) from $t \sim 10$ to $\sim 100$ s as Magnetization Increases from $\sigma_0 \sim \Gamma \sim 30$ to $\sim 10^3$
Parameter Space Study

$3 \times 10^{14} \, G < B_{\text{dip}} < 3 \times 10^{16} \, G, \ 1 \, \text{ms} < P_0 < 5 \, \text{ms}, \ \chi = 0, \pi/2$

GRB Energy (ergs)

solid = oblique, dotted = aligned
Average Magnetization
GRB Duration
\[ \sigma_{\text{avg}} \propto L_\gamma^{1-1.5} \]

**Ave Magnetization** $\sigma_{\text{avg}}$

**Ave Wind Power (erg s$^{-1}$)**

**Prediction:**
More Luminous / Energetic GRBs ⇔ Higher $\Gamma$
\[ \sigma_{\text{avg}} \propto L_{\gamma}^{1-1.5} \]

Prediction:
More Luminous / Energetic GRBs \( \iff \) Higher \( \Gamma \)

\[ \text{Ave Peak Energy} \quad E_{\text{peak}} \propto L_{\text{iso}}^{0.11} \sigma_{0}^{0.2} \varepsilon^{0.33} \]

Agreement with
\[ E_{\text{peak}} \propto E_{\text{iso}}^{0.4} \] (Amati+02)

and
\[ E_{\text{peak}} \propto L_{\text{iso}}^{0.5} \] (Yonetoku+04)

Correlations

\[ \text{Peak Isotropic Jet Luminosity} \quad (\text{erg s}^{-1}) \]
End of the GRB = Neutrino Transparency

Ultra High-σ Outflow
⇒
- Full Acceleration to $\Gamma \sim \sigma$ Difficult
  (e.g. Tchekovskoy et al. 2009)
- Reconnection Slow
- Internal Shocks Weak
  (e.g. Kennel & Coroniti 1984)

$T_{GRB} \sim T_{\nu \text{ thin}} \sim 10 - 100$ s
Steep Decline Phase

End of the GRB = Neutrino Transparency

Ultra High-\(\sigma\) Outflow

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  (e.g. Kennel & Coroniti 1984)

\[
T_{\text{GRB}} \sim T_{\nu\text{ thin}} \sim 10 - 100 \text{ s}
\]
Late-Time (Force-Free) Spin-Down
Willingale et al. 2007 `Plateau'

Time after trigger (s)

X-ray Afterglow

Late-Time (Force-Free) Spin-Down

$\tau_{SD}$

e.g. Zhang & Meszaros 2001; Troja et al. 2007; Yu et al. 2009; Lyons et al. 2010
Plateau Duration - Luminosity Correlation

Data from Lyons et al. 2010
The Diversity of Magnetar Birth

Classical GRB

\[ E_\gamma \sim 10^{50-52} \text{ ergs}, \quad \tau_{\text{jet}} < 1, \quad \Gamma \sim 10^2-10^3 \]

Low-Luminosity GRB

Thermal-Rich GRB (XRF?)

\[ E_\gamma \sim 10^{50} \text{ ergs}, \quad \tau_{\text{jet}} \sim 1, \quad \Gamma < 10 \]
Alternative Formation Channels

Accretion-Induced Collapse (AIC) (Usov 1992; Metzger et al. 2008)

$\Omega$

O-Ne WD

Binary Neutron Star Mergers

$\Omega$

NS

$\Omega$

NS

$t_{\text{visc}} \sim 0.1 \left( \frac{\alpha}{0.1} \right)^{-1} \left( \frac{r}{100 \text{ km}} \right)^{3/2} \left( \frac{h/r}{0.5} \right)^{-2} \text{ sec}$

$M \sim 0.01-0.1 M_\odot$

$R \sim 100 \text{ km}$
GRB 050709

Extended Emission

Time-Averaged Light Curve

Jet Break-Out

Optically-Thick

Optically-Thin

\[ \dot{E}_{\text{jet}} \]

\[ L_{\text{iso}} [10^{50} \text{ ergs s}^{-1}] \]

\[ t = t_{\text{bo}} \]

\[ L_{\text{mag}} \]

\[ t_{\text{obs}}(1+z) [\text{s}] \]

Extended Emission

WXM Counts [2-25 keV]

Seconds Since GRB050709 Trigger
Recap - Constraints on the Central Engine

✓ GRB Duration ~ 10 - 100 seconds & Steep Decay Phase
  - Time until NS to become optically thin to neutrinos

✓ Energies - $E_{\text{GRB}} \sim 10^{50-52}$ ergs
  - Frac of rotational energy lost in ~10-100 s (rad. efficiency ~30-50%)

✓ Ultra-Relativistic Outflow with $\Gamma \sim 100-1000$
  - Mass loading set by physics of neutrino heating (not fine-tuned).

✓ Jet Collimation
  - Exploding star confines and redirects magnetar wind into jet

✓ Association with Energetic Core Collapse Supernovae
  - $E_{\text{rot}} \sim E_{\text{SN}} \sim 10^{52}$ ergs - MHD-powered SN associated w magnetar birth.

✓ Late-Time Central Engine Activity
  - Residual rotational (plateau) or magnetic energy (flares)
Predictions and Constraints

• **Max Energy** - $E_{\text{GRB, Max}} \sim \text{few } 10^{52} \text{ ergs}$
  - So far consistent with observations (but a few Fermi bursts are pushing this limit.)
  - Precise measurements of $E_{\text{GRB}}$ hindered by uncertainties in application of beaming correction.

• **Supernova should *always* accompany GRB**
  - So far consistent with observations.

• **$\Gamma$ increases monotonically during GRB and positively correlate with $E_{\text{GRB}}$**
  - Testing will requires translating jet properties (e.g. power and magnetization) into gamma-ray light curves and spectra.
Summary

• Long duration GRBs originate from the deaths of massive stars, but whether the central engine is a BH or NS remains unsettled.

• Almost all central engine models require rapid rotation and strong magnetic fields. Assessing BH vs. NS dichotomy must self-consistently address the effects of these ingredients on core collapse.

• The power and mass-loading of the jet in the magnetar model can be calculated with some confidence, allowing the construction of a `first principles’ GRB model.

• The magnetar model provides quantitative explanations for the energies, Lorentz factors, durations, and collimation of GRBs; the association with hypernova; and, potentially, the steep decay and late-time X-ray activity.

• Magnetic dissipation is favored over internal shocks and the emission mechanism because it predicts a roughly constant spectral peak energy and reproduces the Amati-Yonetoku correlations.