The Collapsar Model for Gamma-Ray Bursts*

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Shortest 6 ms
GRB 910711

Longest ~2000 s
GRB 971208

Koveliotou (2002)
The majority consensus:

- “Long-soft” bursts are at cosmological distances and are associated with star forming regions

GRB Redshift Distribution, May 2002

mean = 1.27
median = 0.99

27 Total

Djorgovski et al (2002)
Djorgovski et al (2002)

Location of GRBs Within Their Host Galaxies
• GRBs are produced by highly relativistic flows that have been collimated into narrowly focused jets
Minimum Lorentz factors for the burst to be optically thin to pair production and to avoid scattering by pairs.

\[ \Gamma \geq 200 \]

GRBs have total energies not too unlike supernovae

Despite their large inferred brightness, it is increasingly believed that GRBs are not inherently much more powerful than supernovae.

From afterglow analysis, there is increasing evidence for a small "beaming angle" and a common total jet energy near $3 \times 10^{51}$ erg (for a conversion efficiency of 20%).


Bloom, Frail, & Sari
AJ, 121, 2879 (2001)

Piran et al. astro/ph 0108033
Panaitescu & Kumar,
• We may see a hundred unusual supernovae without any strong classical gamma-ray bursts for every one we see with a (strong classical) gamma-ray burst (though there may be weak bursts visible if the star is nearby)

  Very approximately 1% of all supernovae make GRBs but we only see about 0.5% of all the bursts that are made – a rare phenomenon

• If typical GRBs are produced by massive stars, the star must have lost its hydrogen envelope before it died.

  A jet that loses its power source after the mean duration of 10 s can only traverse 3 x 10^{11} cm. This is long enough to escape a Wolf-Rayet star but not a giant.

  ⇒ Not SN II!
A smaller majority would also favor a direct observational connection between supernovae and GRBs

• “Bumps” seen in the optical afterglows of at least three GRBs - 970228, 980326, and 011121 – at the time and with a brightness like that of a Type I supernova


• Coincidence between GRB 980425 and SN 1988bw

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SN 1998bw/GRB 980425


Type Ic supernova, d = 40 Mpc
Modeled as the $3 \times 10^{52}$ erg explosion of a massive CO star
(Iwamoto et al 1998; Woosley, Eastman, & Schmidt 1999)

GRB $8 \times 10^{47}$ erg; 23 s

WFC error box (8') for GRB 980425 and two NFI x-ray sources. The IPN error arc is also shown.
Summary Requirements
(long-soft bursts)

• Provide adequate energy at high Lorentz factor ($\Gamma > 200$; KE $\sim 3 \times 10^{51}$ erg)

• Collimate the emergent beam to approximately 0.1 radians

• Make bursts in star forming regions

• In the internal shock model, provide a beam with rapidly variable Lorentz factor

• Allow for the observed diversity seen in GRB light curves

• Last approximately 20 s, but much longer in some cases

• Explain diverse events like GRB 980425

• Produce a (Type Ib/c) supernova in some cases

• Make x-ray lines of Fe and intermediate mass elements
• It is also the consensus that the root cause of these energetic phenomena is star death that involves an unusually large amount of angular momentum \((j \sim 10^{16} - 10^{17} \text{ cm}^2 \text{ s}^{-1})\) and quite possibly, one way or another, ultra-strong magnetic fields \((\sim 10^{15} \text{ gauss})\). These are exceptional circumstances.

Prompt models:

Milliseccond magnetars

Delayed models (seconds to years):

Jet formation by either a black hole plus accretion disk or an energetic pulsar.
### 15 M☉ Helium Star

<table>
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<th>magnetic fields</th>
<th>rotation (% Keplarian)</th>
<th>mass loss</th>
<th>pulsar period (ms)</th>
<th>$a_{BH}$ (2 M☉)</th>
<th>$a_{BH}$ (2.5 M☉)</th>
<th>$a_{BH}$ (3 M☉)</th>
<th>$a_{BH}$ (4 M☉)</th>
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<td>0.18</td>
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<td>(1.3)</td>
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<td>(1.2)</td>
<td>(1.4)</td>
<td>(1.4)</td>
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<td>0.16</td>
<td>0.14</td>
<td>0.16</td>
<td>0.17</td>
<td></td>
<td>7.4 – 8.8</td>
</tr>
</tbody>
</table>

The ms Magnetar Model:

During the first second following iron core collapse the accretion rate is \( \sim 0.1 \) to \( 1 \, M_\odot \, \text{sec}^{-1} \).

For \( B^2 / 8\pi \sim \rho \, v^2 \) at 30 km with \( v \sim 10^9 \, \text{cm s}^{-1} \), one needs \( B \sim 10^{15} \) gauss.

But now there exist magnetars and AXPs.

For centrifugal force to matter and for the rotational kinetic energy to exceed \( \sim 10^{52} \) erg, one needs a period \( \sim 1 \, \text{ms} \) (and a radius \( \sim 10 \, \text{km} \)).

But this much angular momentum is needed in all modern GRB models.
The ms Magnetar Model:

Assuming the emission of high amplitude ultra-relativistic MHD waves, one has a radiated power

\[ P \sim 6 \times 10^{49} \ (1 \text{ ms/P})^4 \ (B/10^{15} \ \text{ gauss})^2 \ \text{erg s}^{-1} \]

and a total rotational kinetic energy

\[ E_{rot} \sim 4 \times 10^{52} \ (1 \text{ ms/P})^2 \ (10 \text{ km/R})^2 \ \text{erg} \]
Critical Comments on ms magnetar model:

• Not by itself a GRB model (though it could be a SN model – Gunn, Ostriker, Bisnovoty-Kogan, Kundt, Meier, Wilson, Wheeler, etc)

  Isotropic explosion would be not lead to adequate material with high Lorentz factor (even with $10^{53}$ erg – Tan, Matzner, & McKee 2001)

  Jetted explosion would require too much momentum (and too much baryons) to achieve high Lorentz factor. Need to wait for polar regions to “clear”, but during that time the neutron star would probably become a black hole.

  Jets, by themselves are inefficient at producing $^{56}$Ni.
Models with a delay:

Supranovae

Collapsars
“Supranovae”

• First an otherwise normal supernova occurs leaving behind a neutron star whose existence depends on a high rotation rate. \( \Delta M/M \leq 20\% \) Shapiro (2000); Salgado et al (1994)

• The high rotation rate (~ 1 ms) is braked by pulsar-like radiation until a critical angular momentum is reached

• The star then collapses on a dynamic time scale to a black hole leaving behind a disk \( \sim 0.1 M_\odot \) (this is not agreed to by all)

• Accretion of this disk produces a delayed GRB (time scales of order a year) much as in the merging neutron star model
Supranova

**Favorable**

- Produces GRB in a “clean environment
- May explain the existence of x-ray lines in the afterglows of some bursts where large masses of heavy elements are required at large distances
- Requirements in terms of angular momentum no more extreme than other models

**Problematic**

- Would expect a large range in delay times
- Would not give a supernova whose light curve peaked 2 – 3 weeks after the GRB
- Detailed models lacking
- Cannot use star or disk to collimate outflow
Merging Neutron Stars INSIDE Supernova

Suppose have even more angular momentum and a massive proto-neutron star spins apart into pieces during the collapse.

Reassemble up to 10 hours (!) later. Make disk around a black hole.

But what holds up the rest of the collapsing star while all this is going on?

Needs work.
Collapsars

A rotating massive star whose core collapses to a black hole and produces an accretion disk.

<table>
<thead>
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<th>Type</th>
<th>Mass/sun(He)</th>
<th>BH</th>
<th>Time Scale</th>
<th>Distance</th>
<th>Comment</th>
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<td>15-40 He</td>
<td>prompt</td>
<td>20 s</td>
<td>all z</td>
<td>neutrino-dominated disk</td>
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<tr>
<td>II</td>
<td>10-40 He</td>
<td>delayed</td>
<td>20 s – 1 hr</td>
<td>all z</td>
<td>black hole by fall back</td>
</tr>
<tr>
<td>III</td>
<td>&gt;130 He</td>
<td>prompt</td>
<td>~20 s</td>
<td>z&gt;10?</td>
<td>time dilated, redshifted</td>
</tr>
</tbody>
</table>

Type I is what we are usually talking about.
The 40 solar mass limit comes from assuming that all stars above 100 solar masses on the main sequence are unstable (except Pop III).
Collapsar Progenitors

Two requirements:

- Core collapse produces a black hole - either promptly or very shortly thereafter.

- Sufficient angular momentum exists to form a disk outside the black hole (this virtually guarantees that the hole is a Kerr hole)

In the absence of mass loss and magnetic fields, there would be abundant progenitors.

Unfortunately nature has both.

The more difficult problem is the angular momentum. This is a problem shared by all current GRB models that invoke massive stars...
With decreasing metallicity, the binding energy of the core and the size of the silicon core both increase, making black hole formation more likely at low metallicity.

Woosley, Heger, & Weaver, RMP, (2002)
Some implications ....

• The production of GRBs may be favored in metal-deficient regions, either at high red shift or in small galaxies (like the SMC). The metallicity-dependence of mass loss rates for RSGs is an important source of uncertainty. (Kudritzky (2000); Vink, de Koters, & Lamers A&A, 369, 574, (2001))

• But below some metallicity $Z$ about, 0.1, single massive stars will not make GRBs because they do not lose their hydrogen envelope.

• GRBs may therefore not track the total star formation rate, but of some special set of stars with an appreciable evolutionary correction.
Given the necessary angular momentum, black hole formation is accompanied by disk formation...
The Star Collapses ($\log j > 16.5$)

$\alpha = 0.1$

$\alpha = 0.001$

Neutrino flux high, $^{56}$Ni high

Neutrino flux low, $^{56}$Ni low

The star collapses and forms a disk ($\log j > 16.5$)

In the vicinity of the rotational axis of the black hole, by a variety of possible processes, energy is deposited.

It is good to have an energy deposition mechanism that proceeds independently of the density and gives the jet some initial momentum along the axis

7.6 s after core collapse; high viscosity case.

MacFadyen & Woosley (1998)
The Neutrino-Powered Model (Type I Collapsar Only)

Given the rather modest energy needs of current central engines ($3 \times 10^{51}$ erg?) the neutrino-powered model is still quite viable and has the advantage of being calculable.

A definitive calculation of the neutrino transport coupled to a realistic multi-dimensional hydrodynamical model is still lacking.

MacFadyen & Woosley (1999)

Fryer (1998) about a solar luminosity per cubic meter!
MHD Energy Extraction

From the rotational energy of the black hole:

$$\dot{E} \sim 0.4 \frac{B^2 r_s^2 c}{\mu_0} \sim 4 \times 10^{52} B_{15}^2 \left(\frac{M}{10 M_\odot}\right)^2 \text{ erg s}^{-1}$$

But only need $\sim 4 \times 10^{50} \text{ erg s}^{-1}$!

The efficiencies for converting accreted matter to energy need not be large. $B \sim 10^{14} - 10^{15}$ gauss for a 3 solar mass black hole. Well below equipartition in the disk.

Eventually shuts off when $\dot{M}$ can no longer sustain such a large B-field.

Blandford & Znajek (1977)
Koide et al. (2001)
van Putten (2001)
Lee et al (2001)
etc.
The jet is initially collimated by the density gradient left by the accretion.

It will not start until the ram pressure has declined below a critical value.
The Production of $^{56}\text{Ni}$

• Needed to power the light curve of the supernova if one is to be visible. Need 0.1 to 0.5 solar masses of it.

• A bigger problem than most realize
  The jet doesn’t do it – too little mass
  Forming the black hole depletes the innermost core of heavy elements
  Pulsars may have a hard time too if their time scale is $> 1$ ms
Neglecting electron capture in the disk
Electron capture in the Disk

Popham, Woosley, & Fryer (1999)

<table>
<thead>
<tr>
<th>$\dot{M}$ (M$_\odot$ s$^{-1}$)</th>
<th>$\alpha$</th>
<th>$Y_{ec}$</th>
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<td>0.05</td>
</tr>
<tr>
<td>0.1</td>
<td>0.03</td>
<td>0.12</td>
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</table>
The Jet-Star Interaction
Initiate a jet of specified Lorentz factor (here 50), energy flux (here $10^{51}$ erg/s), and internal energy (here internal $E$ is about equal to kinetic energy), at a given radius (2000 km) in a given post-collapse (7 s) phase of 15 solar mass helium core evolved without mass loss assuming an initial rotation rate of 10% Keplerian. The stars radius is $8 \times 10^{10}$ cm. The initial opening angle of the jet is 20 degrees.
Relativistic Jets From Collapsars

S.E. Woosley's Group

Initial Model: he15

480 radial zones, 200 angular zones

Energy Deposition Rate: $10^{51}$ ergs/s

Half Opening Angle: 20

$f_e(E_{th}/E_{tot})$: 0.67

Lorentz Factor: 50
Independent of initial opening angle, the emergent beam is collimated into a narrow beam with opening less than 5 degrees (see also Aloy et al. 2000)
The previous calculation was 2D in spherical coordinates. This puts all the resolution near the origin and also spends a lot of zones following the unshocked star.

Repeat using cylindrical coordinates and study the just the jet’s interactions with finer zoning – but keeping the same density and temperature structure as in the star along its rotational axis. Carry 80,000 km = 10% of the star.

150 x 800 zones; zone size 100 km
R_i = 2000 km
initial jet radius = 700 km (20 deg at 2000 km)
Γ = 10
E_{int} / KE = 20
\dot{E} = 5 \times 10^{50} \text{ erg s}^{-1}
Pressure at 2.2 seconds
Lessons Learned

• Even a jet of constant power is strongly modulated by its passage through the star.

• The variations in Lorentz factor and density can be of order unity.

• An initially collimated jet stays collimated.

• There may be important implications for the light curve – especially its time structure.
Jet Break Out
and Spreading
PARTICULARS

zoning: cylindrical grid 1500 x 2275 zones
  \( r = 0 \) to \( 6 \times 10^{11} \) cm
  \( z = 1.0 \times 10^{10} \) to \( 2.0 \times 10^{12} \) cm

\( \Delta r = 10^8 \) cm for \( r = 0 \) to \( 10^{11} \) cm
  \( 4 \times 10^8 \) cm for \( r = 10^{11} \) to \( 2 \times 10^{11} \) cm
  \( 1.6 \times 10^9 \) cm for \( r = 2 \times 10^{11} \) to \( 6 \times 10^{11} \) cm

\( \Delta z = 10^8 \) cm for \( z = 10^{10} \) to \( 10^{11} \) cm
  \( 4 \times 10^8 \) cm for \( z = 10^{11} \) to \( 2 \times 10^{11} \) cm
  \( 1.6 \times 10^9 \) cm for \( z = 2 \times 10^{11} \) to \( 2 \times 10^{12} \) cm

Model A \((6 \times 10^{51} \) erg\)
  \( E = 3 \times 10^{50} \) erg s\(^{-1}\)
  \( \Gamma = 5 \)
  \( f_0 = 40 \)
  for 20 s then linear decline to 0 at 30 s

Model B \((2 \times 10^{51} \) erg\)
  \( E = 10^{50} \) erg s\(^{-1}\)
  \( \Gamma = 10 \)
  \( f_0 = 20 \)
  for 20 s then ....

Fine zoned 15 solar mass helium star.
\( R = 8 \times 10^{10} \) cm
The jet approaches the surface: Maximum Lorentz factors are mild - $\Gamma \sim 10$, but the internal energy loading is high, also $\sim 10$
Model A - 11 seconds
at break out

note the mildly relativistic cocoon
Density structure at break out

Note plug!
Note large internal energy loading in the cocoon as well as in the jet.
Mass fraction of jet material
Model A
Model A

Total energy $\Gamma > 5$
Model B

$\Gamma > 5$

Total energy
A Unified Model for Cosmological Transients
(analogous to AGNs)
Short-Hard Bursts

*A Speculation*

The equivalent isotropic energy contained in the “plug” and in other dense material near the axis is about $10^{51}$ erg. This is the energy of a “short hard burst”.

The Lorentz factor of this material is about 20 at the last calculation (70 s, $10^{12}$ cm). Might this make a short-hard burst (by external shock interaction)?

**Predictions:**

- Short hard bursts in association with massive stars
- Short hard bursts and long soft bursts mixed together
The Jet Explodes the Star

Continue the spherical calculation for a long time, at least several hundred seconds. See how the star explodes, the geometry of the supernova, and what is left behind.

Inner radius = $2 \times 10^8$ cm
Outer radius = $10^{12}$ cm
$\Gamma = 10$ for 20 seconds then declines to 2 at 1000 sec
$\dot{E} = 5 \times 10^{50}$ erg s$^{-1}$ declining to $10^{47}$ erg s$^{-1}$ at 1000 s
$E_{\text{int}} / KE = 20$ declining to 2 at 1000 sec
$\theta_o = 20^\circ$
Density and radial velocity at 80 s (big picture)
Zoom in by 5...
The shock has wrapped around and most of the star is exploding. Outer layers and material along the axis moves very fast. Most of the rest has more typical supernova like speeds $\sim 3000 - 10,000 \text{ km s}^{-1}$.
(Zoom in *100)

But shown on a magnified scale, there is still a lot of dense low velocity material near the black hole
The shock has wrapped around and the whole star is exploding (initial radius was less than one tick mark here). A lot of matter in the equatorial plane has not achieved escape velocity though and will fall back. Continuing polar outflow keeps a channel open along the rotational axis.
By this time the star has expanded to over ten times its initial radius the expansion has become (very approximately) homologous. Provided outflow continues along the axis as assumed, an observer along the axis (i.e., one who saw a GRB) will look deeper into the explosion and perhaps see a bluer supernova with broader lines (e.g., SN2001ke; Garnavich et al. 2002).

Continued accretion is occurring in the equatorial plane.

**Caution: Effect of disk wind not included here**
Some Implications:

- The “opening angle” will increase with time as the jet blows the outer part of the star away. There may not be a single $\theta_{\text{jet}}$, but one that evolves with time. $\theta_{\text{jet}}$ may be bigger for afterglows than for GRBs.

- The energy input by continuing accretion during the first day may still be very appreciable, perhaps even exceeding that in the active GRB producing phase. This may be output as mildly relativistic matter. The energy measured from afterglows may exceed appreciably what the GRB actually required.

- There will be a continuing energy source for powering lines at late times as assumed by e.g., Meszaros and Rees.

- Bursts may have long “tails” of continuing activity.
Some Conclusions:

- The light curves of (long-soft) GRBs may reflect more the interaction of the jet with the star than the time variability of the engine itself.

- The emergent jet in the collapsar model may still contain a large fraction of its energy as internal energy. Expansion after break out, of material with Lorentz factor of order 10 can still give final Lorentz factors over 100.

- Much weaker bursts are expected off axis (GRB 980425?, x-ray flashes?)

- Jet powered supernovae may have significant equatorial fall back. Jet may continue with a declining power for a long time – even days

- Short hard bursts might be made by collapsars