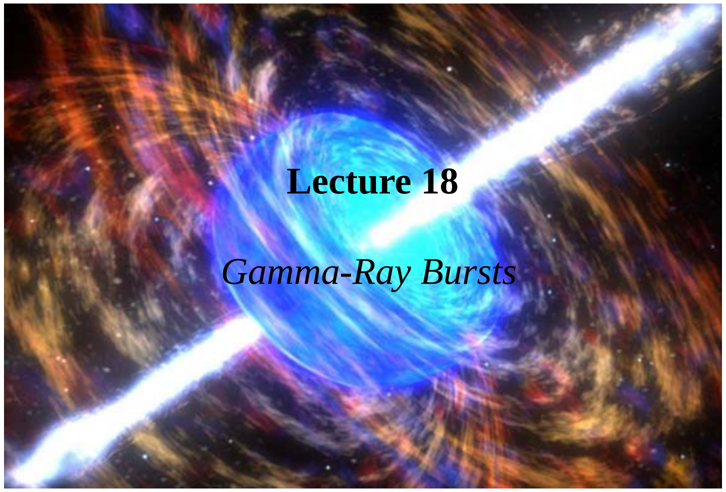
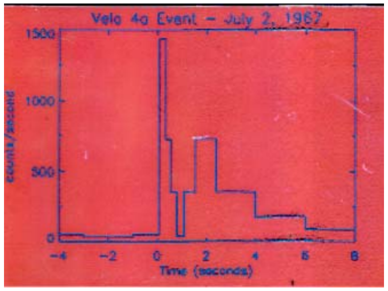


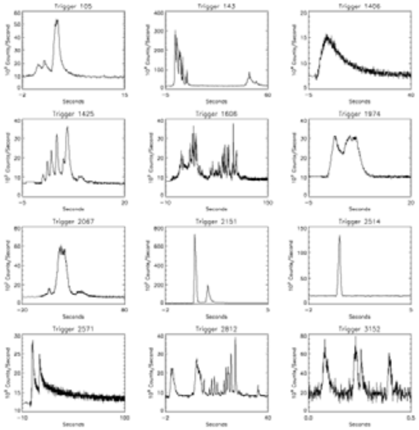
Lecture 18

Gamma-Ray Bursts

First Gamma-Ray Burst



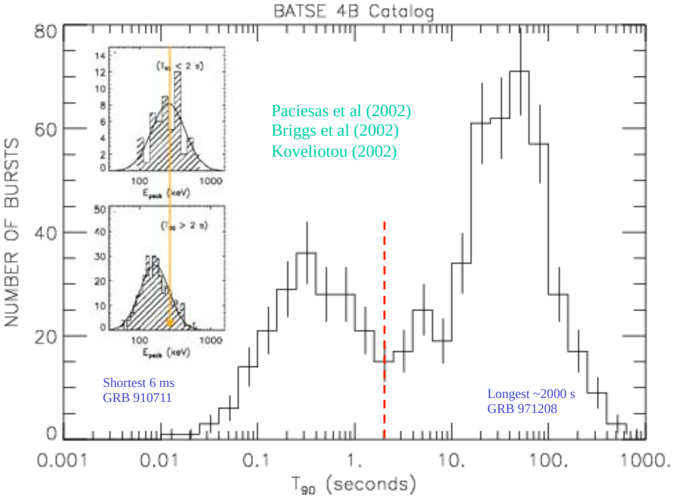
The Vela 5 satellites functioned from July, 1969 to April, 1979 and detected a total of 73 gamma-ray bursts in the energy range 150 – 750 keV (n.b,. Greater than 30 keV is gamma-rays). Discovery reported Klebesadel, Strong, and Olson (1973).



Typical durations are 20 seconds but there is wide variation both in time-structure and duration.

Some last only hundredths of a second. Others last thousands of seconds.

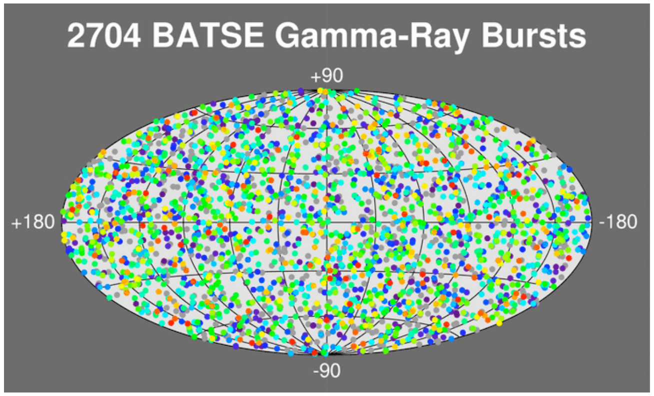
Typical power spectra peak at 200 keV and higher.



Paciesas et al (2002)
Briggs et al (2002)
Koveliotou (2002)

Shortest 6 ms
GRB 910711

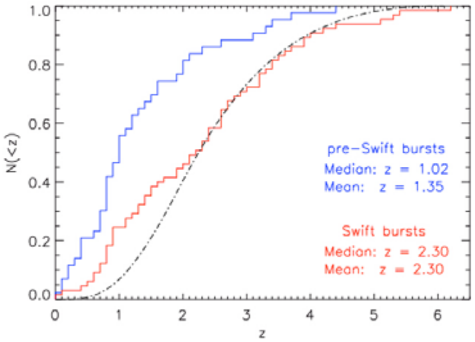
Longest ~2000 s
GRB 971208



In total about 5000 gamma-ray bursts have been detected

Skipping over a rich history here

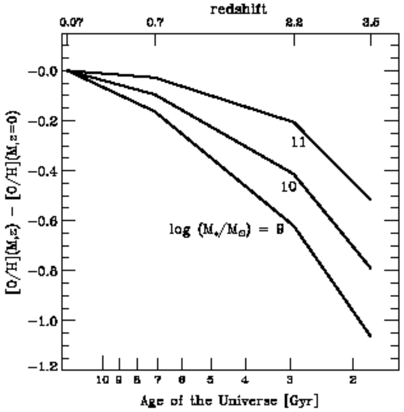
- Most bursts discovered so far (though not necessarily per fixed volume) are LSB's at cosmological distances.



As of April, 2008
131 bursts

SWIFT gives an average z about twice as great

www.astro.ku.dk/~pallja/GRBsample.html



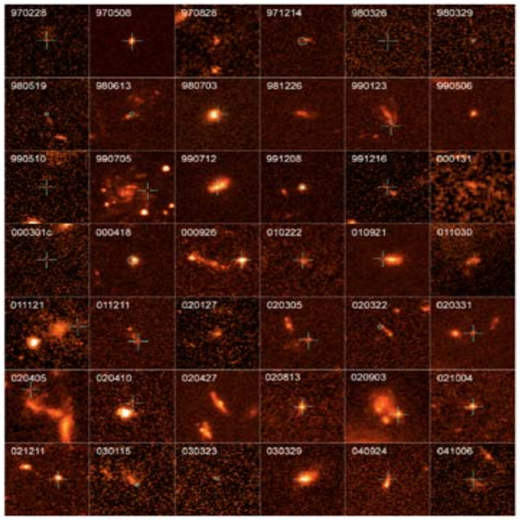
Maiolino et al (2008)
astroph0806-2410

AMAZE Survey
ESO-VLT

Z ~ 2 - 3 is an era of intense evolution for the SN rate and the metallicity

Metallicity in low M galaxies rises slower than in high M

nb. Z here is oxygen, not Fe; Fe/O declines with decreasing Z

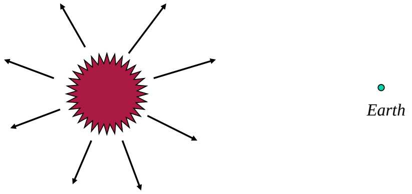


Fruchter et al. (2006)

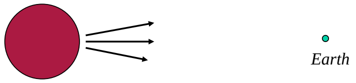
LSGRBs are found in star-forming galaxies. Their location within those galaxies is associated with the light with a tighter correlation than even Type Iip supernovae (but maybe not Type Ic).

At these distances gamma-ray bursts would have an energy of 10^{52} erg to 10^{54} erg if they emitted isotropically. That is up to the rest mass of the sun turned into gamma-rays in 10 seconds!

But the energies required are not really that great

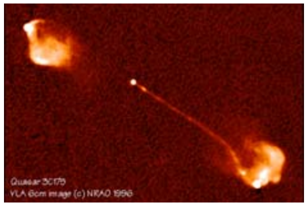


If the energy were beamed to 0.1% of the sky, then the total energy could be 1000 times less

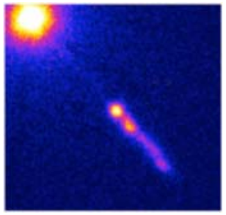


Nothing seen down here

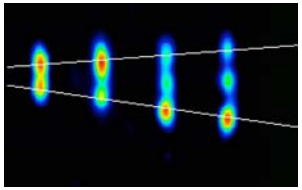
- GRBs are produced by highly relativistic flows that have been collimated into narrowly focused jets



Quasar 3C 175 as seen in the radio

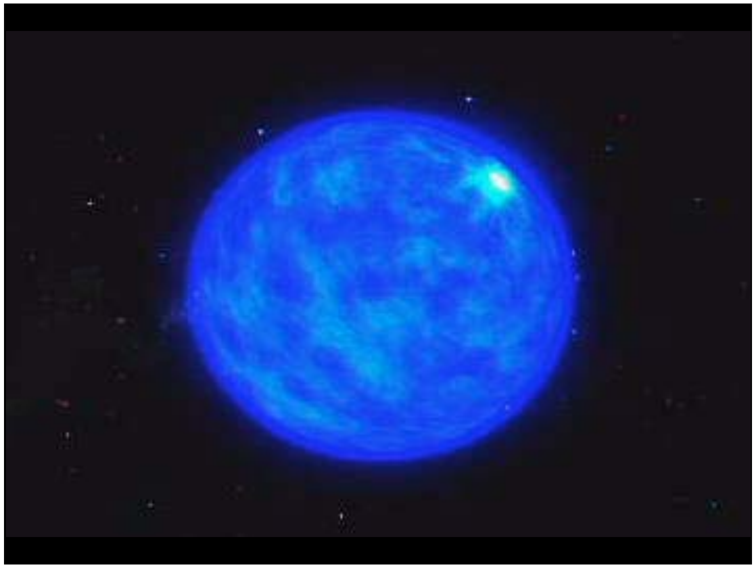


Quasar 3C273 as seen by the Chandra x-ray Observatory



Microquasar GPS 1915
in our own Galaxy – time sequence

Artist's conception of SS433 based on observations



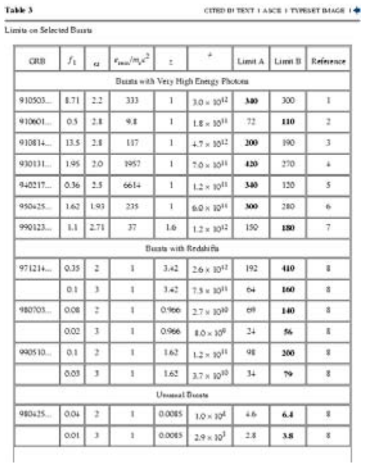


Table 3 CITED IN TEXT | ASCII | TYPESET IMAGE |

Limits on Selected Bursts

GRB	f_1	α	$\epsilon_{max}/m_e c^2$	z	$\hat{\tau}$	Limit A	Limit B	Reference
Bursts with Very High Energy Photons								
910503...	8.71	2.2	333	1	3.0×10^{12}	**340**	300	1
910601...	0.5	2.8	9.8	1	1.8×10^{11}	72	**110**	2
910814...	13.5	2.8	117	1	4.7×10^{12}	**200**	190	3
930131...	1.95	2.0	1957	1	7.0×10^{11}	**420**	270	4
940217...	0.36	2.5	6614	1	1.2×10^{11}	**340**	120	5
950425...	1.62	1.93	235	1	6.0×10^{11}	**300**	280	6
990123...	1.1	2.71	37	1.6	1.2×10^{12}	150	**180**	7
Bursts with Redshifts								
971214...	0.35	2	1	3.42	2.6×10^{12}	192	**410**	8
	0.1	3	1	3.42	7.5×10^{11}	64	**160**	8
980703...	0.08	2	1	0.966	2.7×10^{10}	69	**140**	8
	0.02	3	1	0.966	8.0×10^{9}	24	**56**	8
990510...	0.1	2	1	1.62	1.2×10^{11}	98	**200**	8
	0.03	3	1	1.62	3.7×10^{10}	34	**79**	8
Unusual Bursts								
980425...	0.04	2	1	0.0085	1.0×10^{4}	4.6	**6.4**	8
	0.01	3	1	0.0085	2.9×10^{3}	2.8	**3.8**	8

Minimum Lorentz factors for the burst to be optically thin to pair production and to avoid scattering by pairs.

Lithwick & Sari, ApJ, 555, 540, (2001)

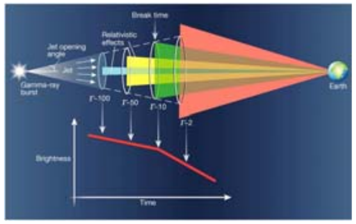
$$\Gamma \geq 200$$

It is a property of matter moving close to the speed of light that it emits its radiation in a small angle along its direction of motion. The angle is inversely proportional to the *Lorentz factor*

$$\Gamma = \frac{1}{\sqrt{1 - v^2/c^2}}, \qquad \textit{E.g.},\ \Gamma = 100 \quad v = 0.99995\,c$$

$$\theta = 1/\Gamma \qquad\qquad \Gamma = 10 \quad v = 0.995\,c$$

This offers a way of measuring the beaming angle. As the beam runs into interstellar matter it slows down.



Measurements give an opening angle of about 5 degrees.

- GRBs have total energies not too unlike supernovae

Frail et al. ApJL, (2001), astro/ph 0102282

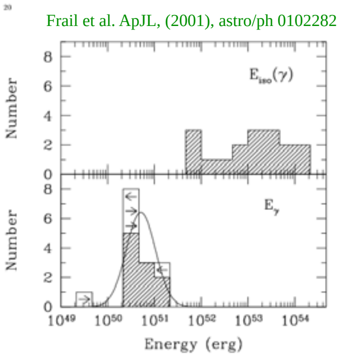


Figure 3. The distribution of the apparent isotropic γ-ray burst energy of GRBs with known redshifts (top) versus the geometry-corrected energy for those GRBs whose afterglows exhibit the signature of a non-isotropic outflow (bottom). The mean isotropic equivalent energy $\langle E_{iso}(\gamma)\rangle$ for 17 GRBs is 110×10^{51} erg with a 1-σ spreading of a multiplicative factor of 6.2. In estimating the mean geometry-corrected energy $\langle E_\gamma\rangle$ we applied the Bayesian inference formalism[49] and modified to handle datasets containing upper and lower limits.[50] Arrows are plotted for five GRBs to indicate upper or lower limits to the geometry-corrected energy. The value of $\langle \log E_\gamma \rangle$ is 50.71 ± 0.10 (1σ) or equivalently, the mean geometry-corrected energy $\langle E_\gamma\rangle$ for 15 GRBs is 0.5×10^{51} erg. The standard deviation in $\log E_\gamma$ is $0.31^{+0.09}_{-0.06}$ or a 1-σ spread corresponding to a multiplicative factor of 2.0.

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

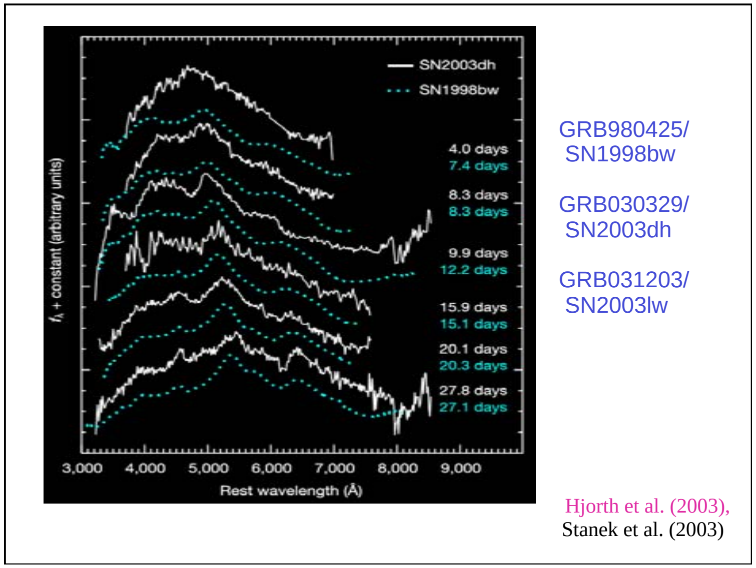
From afterglow analysis, there is increasing evidence for a small "beaming angle" and a common total jet energy near 3 x 10^{51} erg (for a conversion efficiency of 20%).

See also: Freedman & Waxman, ApJ, 547, 922 (2001)

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

Piran et al. astro/ph 0108033

Panaitescu & Kumar, ApJL, 560, L49 (2000)

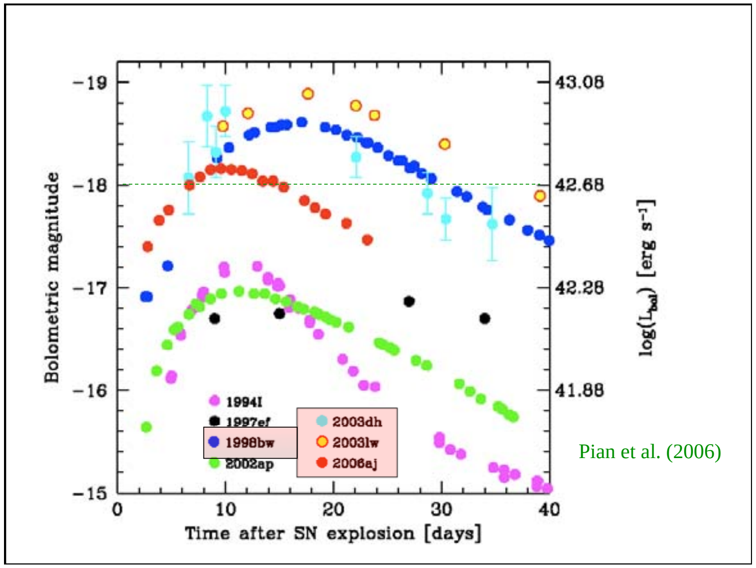


GRB980425/ SN1998bw

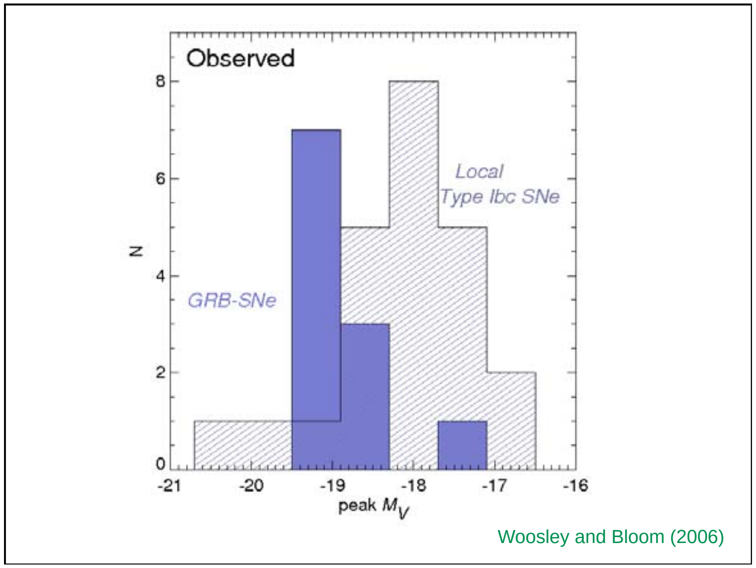
GRB030329/ SN2003dh

GRB031203/ SN2003lw

Hjorth et al. (2003), Stanek et al. (2003)



Pian et al. (2006)



Woosley and Bloom (2006)

- How common are SN Ib/c? Local rate:
  - ~15-20% of all SN
  - ~30% of CC-SN
  - Broad-lined SN Ic (SN Ic-BL): ~5-10% of all SN Ib/c

(Cappellaro et al 1999, Guetta & Della Valle 2007, Leaman et al. in prep)

So SN Ic-BL are 1 - 2% of all supernovae.
GRBs are a much smaller fraction. The distinction may be the speed of core rotation at death (which is correlated with the metallicity)

Not all SN Ic - BL are GRBs
(though they may all be “active” at some level.

The rate at which massive stars die in the universe is very high and GRBs are a small fraction of that death rate.

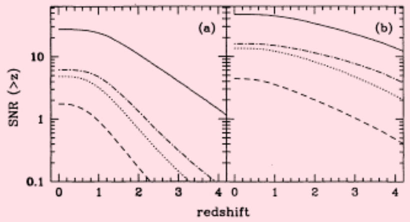


Figure 3. Predicted cumulative number of Type Ia and II(+b/c) SNe above a given redshift z in a 4×4 arcmin^2 field. Solid line: Type II SNe. Dashed-dotted line: Type Ia SNe with $\tau = 0.3$ Gyr. Dotted line: Type Ia SNe with $\tau = 1$ Gyr. Dashed line: Type Ia SNe with $\tau = 3$ Gyr. The effect of dust extinction on the detectability of SNe is negligible in these models. (a) Model predictions of the 'merging' scenario of Fig. 1a. (b) Same for the 'monolithic collapse' scenario of Fig. 1b.

Madau, della Valle, & Panagia, MNRAS, 1998

Supernova rate per 16 arc min squared per year ~20

This corresponds to an all sky supernova rate of

6 SN/sec

*For comparison the universal GRB rate is about 3 /day * 300 for beaming or*

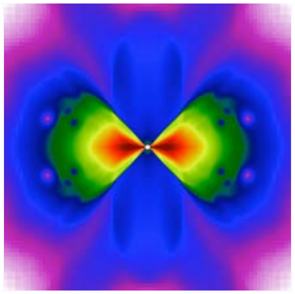
~ 0.02 GRB/sec

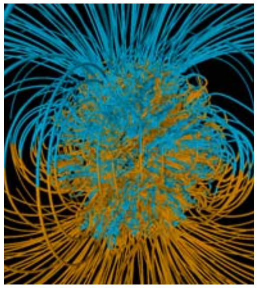
Models

It is the consensus that the root cause of these energetic phenomena is star death that involves an unusually large amount of angular momentum ($j \sim 10^{16} – 10^{17}$ cm^2 s^{-1}) and quite possibly, one way or another, ultra-strong magnetic fields ($\sim 10^{15}$ gauss). These are exceptional circumstances. A neutron star or a black hole is implicated.

Today, there are two principal models being discussed for GRBs of the "long-soft" variety:

- The collapsar model
- The millisecond magnetar





The ultimate source of energy in both is rotation.

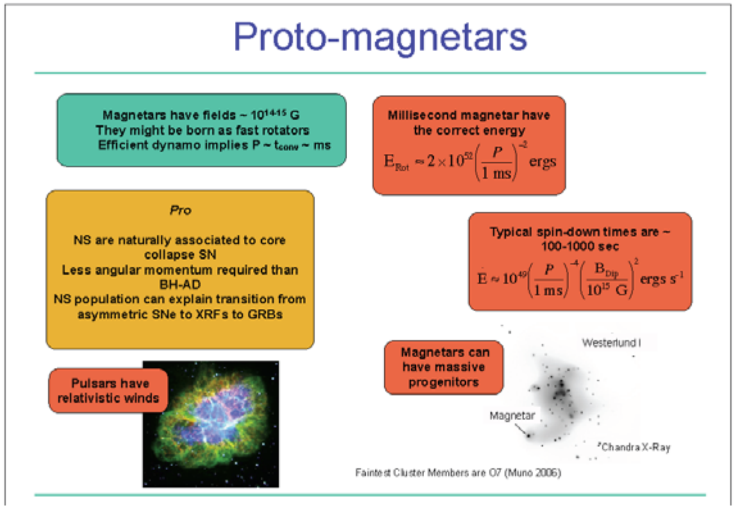
"Predictions" of both the collapsar and magnetar models*

LSBs

- Relativistic jets ✓
- Occur in star forming regions ✓
- Occur in hydrogen-stripped stars and are often accompanied by SN Ibc ✓
- Are a small fraction of SN Ibc ✓ ~0.3% of all SN
- Are favored by low metallicity (and rapid rotation) ✓
- Occur in CSM with density proportional to r^{-2} ?

* Predicted by collapsar model but probably consistent with magnetar model

Magnetar Model



Proto-magnetars

Magnetars have fields ~ $10^{14\text{-}15}$ G
They might be born as fast rotators
Efficient dynamo implies P ~ t_{conv} ~ ms

Millisecond magnetar have the correct energy

$$E_{Rot} \approx 2\times10^{52}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-2}\ \mathrm{ergs}$$

Pro

NS are naturally associated to core collapse SN
Less angular momentum required than BH-AD
NS population can explain transition from asymmetric SNe to XRFs to GRBs

Typical spin-down times are ~ 100-1000 sec

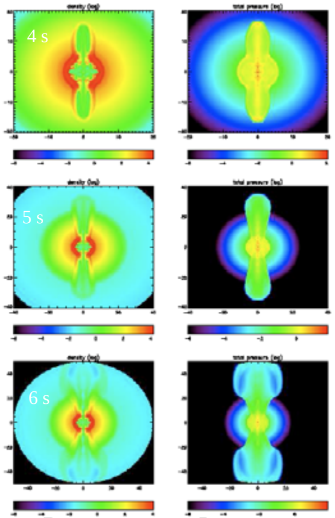
$$\dot{E} \approx 10^{49}\left(\frac{P}{1\ \mathrm{ms}}\right)^{-4}\left(\frac{B_{Dip}}{10^{15}\ \mathrm{G}}\right)^{2}\ \mathrm{ergs\ s^{-1}}$$

Pulsars have relativistic winds

Magnetars can have massive progenitors

Faintest Cluster Members are O7 (Muno 2006)

Slide from N. Bucciantini



Density Pressure

Bucciantini, Quataert, Arons, Metzger and Thompson (MNRAS; 2007) and refs therein, see also Komissarov et al (2008)

Assume a pre-existing supernova explosion in the stripped down core of a 35 solar mass star.

Insert a spinning down 1 ms magnetar with B ~ 10^{15} gauss.

Two phase wind:

Initial magetar-like wind contributes to explosion energy. Analog to pulsar wind. Sub-relativistic

Later magnetically accelerated neutrino powered wind with wound up B field makes jet. Can achieve high field to baryon loading.

The maximum energy available for the supernova and the GRB producing jet in the magnetar model is ~ 2 x 10^{52} erg.

Total rotational kinetic energy for a neutron star

$$E_{rot} \sim 2\times 10^{52}\,(1\ \mathrm{ms/P})^2\ (\mathrm{R}/10\ \mathrm{km})^2\ \mathrm{erg}$$

This is the maximum value for a cold, rigidly rotating neutron star. A proto-neutron star at 10 - 100 ms is neither. Its large entropy makes the radius bigger and E_{rot} less, differential rotation increases E_{rot}. The trade off means that the above limit is not far off. Detailed calculations needed but consistent with Burrows et al.

Major Uncertainties

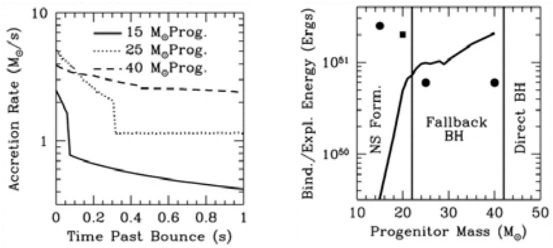
- What launches the supernova that clears the matter away from the vicinity of the neutron star and allows it to operate as in a vacuum?
- What distinguishes magnetar birth from GRBs? Is it a continuum based on rotation rate?
- How is several tenths of a solar mass of ^{56}Ni made?
- Is the energy enough?
- Late time activity

Collapsar Model

Collapsar Progenitors

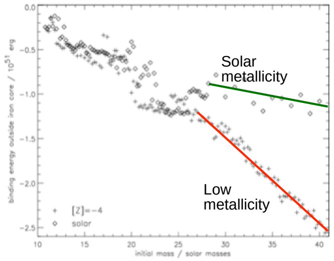
Two requirements:

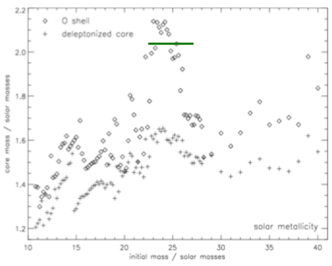
- Core collapse produces a black hole - either promptly or very shortly thereafter.
- Sufficient angular momentum exists to form a disk outside the black hole (this virtually guarantees that the hole is a Kerr hole)



Fryer, ApJ, 522, 413, (1999)

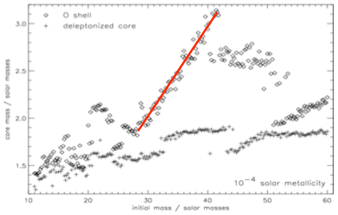
Black hole formation may be unavoidable for low metallicity





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)

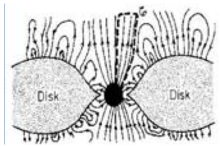


For the last stable orbit around a black hole in the collapsar model (i.e., the minimum j to make a disk)

$$j_{LSO} = 2\sqrt{3}\ GM/c = 4.6\times10^{16}\ M_{BH}/3M_\odot\ \mathrm{cm^2\ s^{-1}}$$ non-rotating

$$j_{LSO} = 2/\sqrt{3}\ GM/c = 1.5\times10^{16}\ M_{BH}/3M_\odot\ \mathrm{cm^2\ s^{-1}}$$ Kerr a = 1

It is somewhat easier to produce a magnetar model!



$a \approx 1$

MHD Energy Extraction

Blandford & Znajek (1977)
Koide et al. (2001)
van Putten (2001)
Lee et al (2001)
etc.

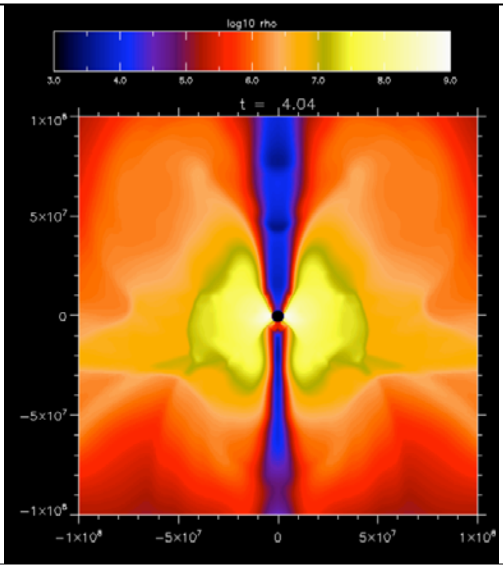
From the rotational energy of the black hole:

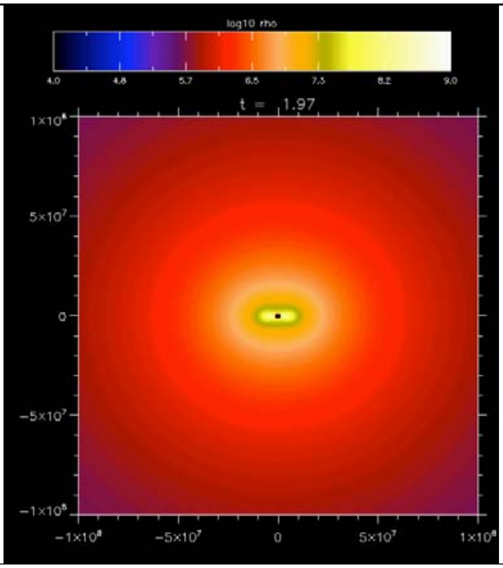
$$\dot{E} \sim 0.4\ \frac{B^2}{\mu_o} r_S^{\,2}\, c \sim 4 \times 10^{52}\ B_{15}^2 \left(\frac{M}{10\ M_\odot}\right)^2 \mathrm{erg\ s^{-1}}$$

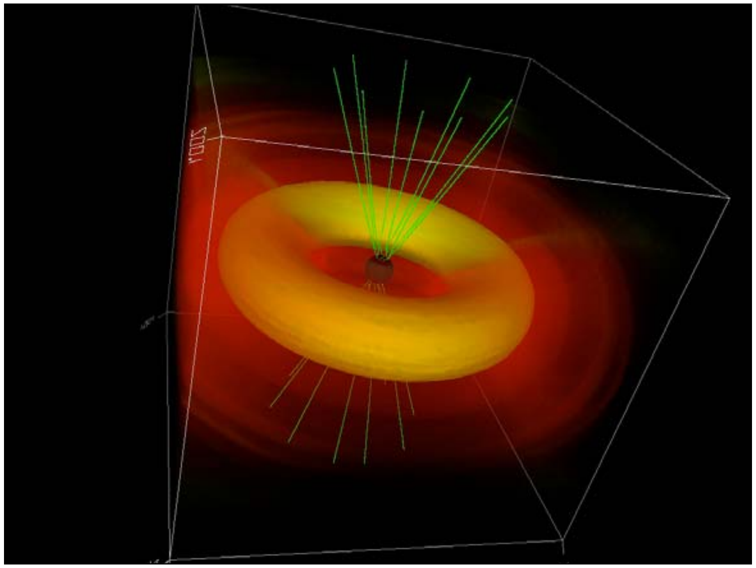
But only need ~ $4\,x 10^{50}$ erg $\mathrm{s^{-1}}$!

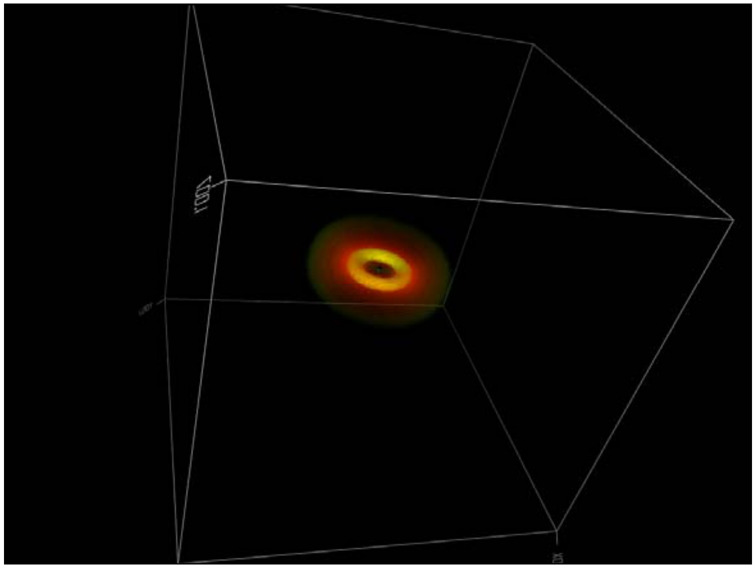
The efficiencies for converting accreted matter to energy need not be large. B ~ 10^{14} – 10^{15} gauss for a 3 solar mass black hole. Well below equipartition in the disk.

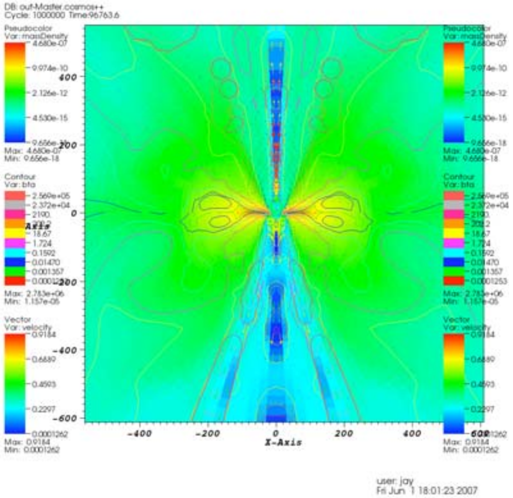
Eventually shuts off when $\dot{M}$ can no longer sustain such a large B-field.





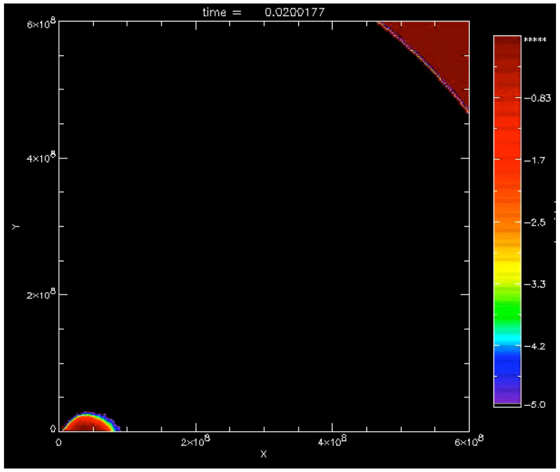


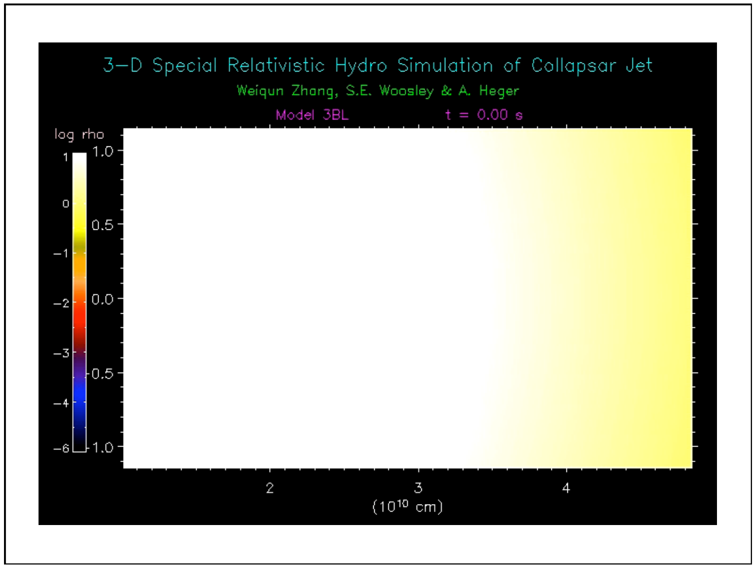


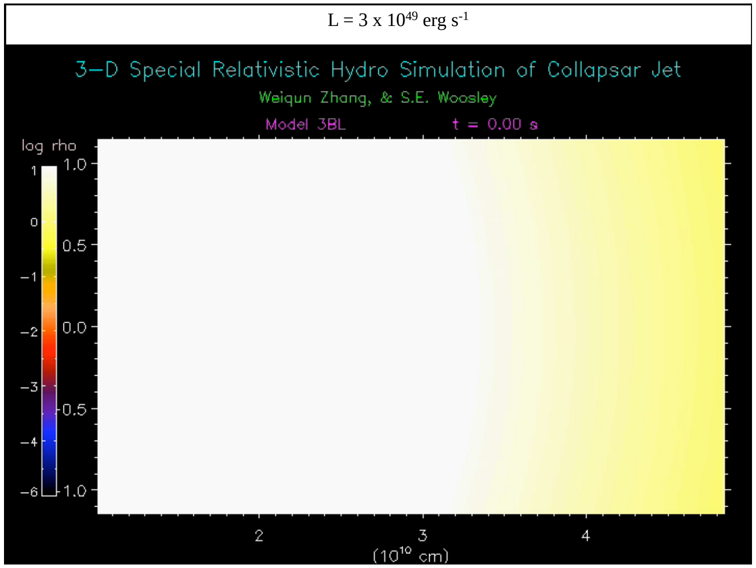


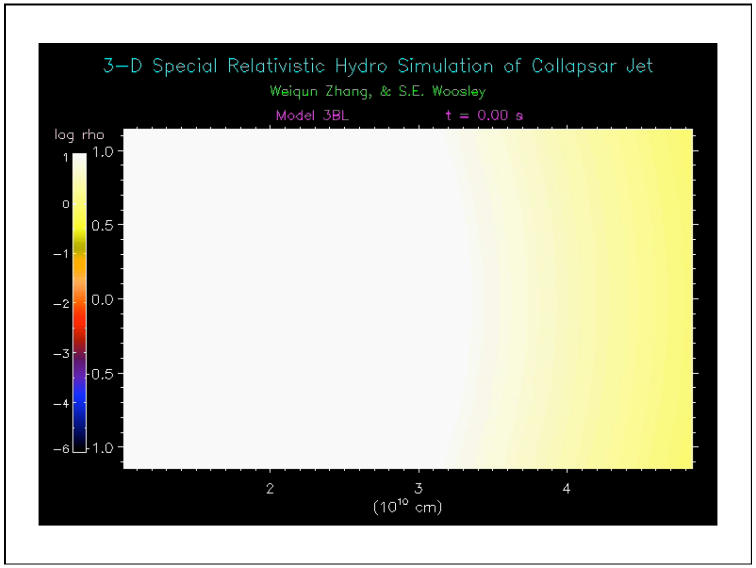
Recent calculation by Jay Salmonson using COSMOS++. Shows magnetically dominated jet formation and also shepharding outflow to 30 degrees.

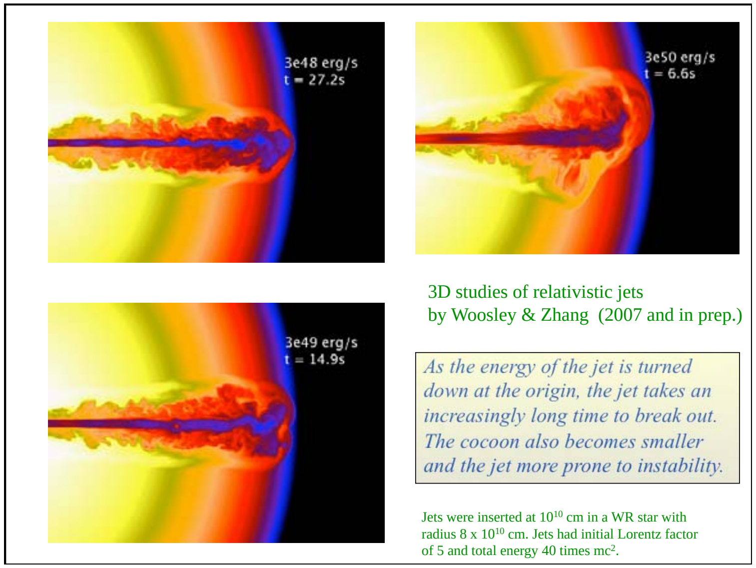
The disk wind: MacFadyen & Woosley (2001)






L = 3 x 10^{49} erg s^{-1}

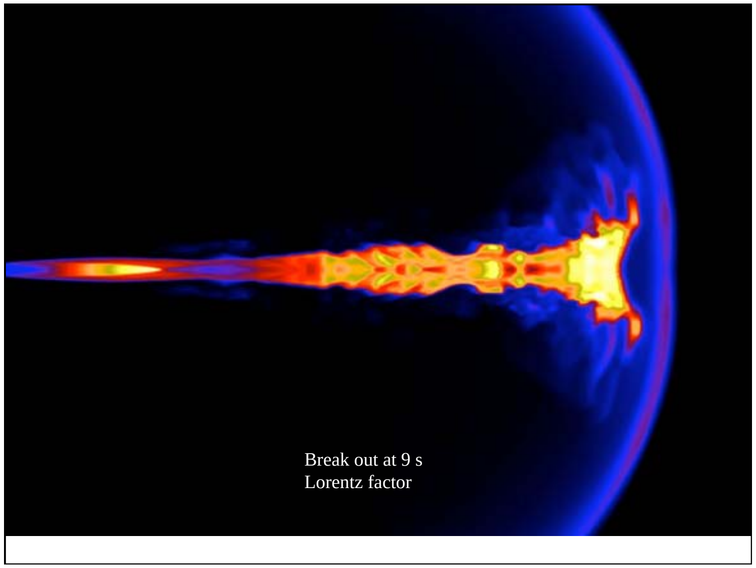




3D studies of relativistic jets
by Woosley & Zhang (2007 and in prep.)

As the energy of the jet is turned down at the origin, the jet takes an increasingly long time to break out. The cocoon also becomes smaller and the jet more prone to instability.

Jets were inserted at 10^{10} cm in a WR star with radius 8 x 10^{10} cm. Jets had initial Lorentz factor of 5 and total energy 40 times mc^2.



How to Get the Necessary Rotation

Need iron core rotation at death to correspond to a pulsar of < 5 ms period if rotation and B-fields are to matter to the explosion. Need a period of ~ 1 ms to make GRBs. This is much faster than observed in common pulsars.

Total rotational kinetic energy for a neutron star

$$E_{rot} \sim 2 \times 10^{52}\,(1\ \mathrm{ms/P})^2\ (\mathrm{R}/10\ \mathrm{km})^2\ \mathrm{erg}$$

$$j = R^2\Omega \sim \boxed{6.3\times10^{15}}\,(1\mathrm{ms/P})(\mathrm{R}/10\ \mathrm{km})^2\ \ \mathrm{cm}^2\ \mathrm{s}^{-1}\ \ \text{at M} \approx 1.4\,M_\odot$$

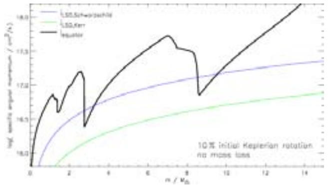
For the last stable orbit around a black hole in the collapsar model (i.e., the minimum j to make a disk)

$$j_{LSO} = 2\sqrt{3}\ \ GM/c = \boxed{4.6\times10^{16}}\,M_{BH}/3M_\odot\ \mathrm{cm}^2\ \mathrm{s}^{-1} \qquad \text{non-rotating}$$

$$j_{LSO} = 2/\sqrt{3}\ \ GM/c = \boxed{1.5\times10^{16}}\,M_{BH}/3M_\odot\ \mathrm{cm}^2\ \mathrm{s}^{-1} \qquad \text{Kerr}\ \ a = 1$$

It is somewhat easier to produce a magnetar model!

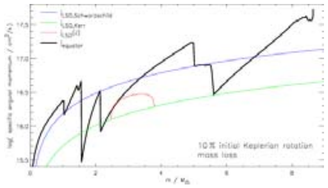
The more difficult problem is the angular momentum. This is a problem shared by all current GRB models that invoke massive stars...

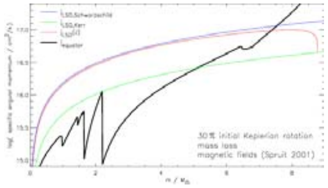


15 solar mass helium core born rotating rigidly at f times break up

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

Unfortunately nature has both.





Stellar evolution including approximate magnetic torques gives slow rotation for common supernova progenitors, i.e., those that make pulsars (solar metallicity)

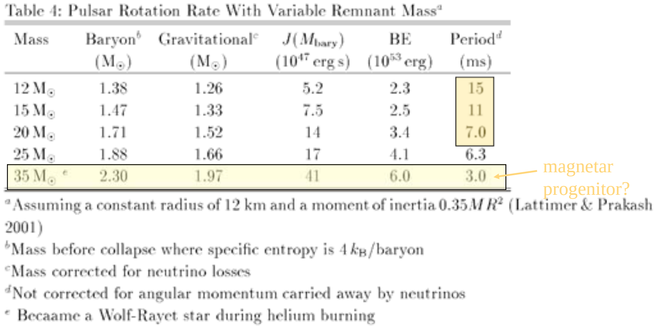


Table 4: Pulsar Rotation Rate With Variable Remnant Mass[a]

Mass	Baryon[b] ($M_\odot$)	Gravitational[c] ($M_\odot$)	$J(M_{\rm bary})$ (10^{47} erg s)	BE (10^{53} erg)	Period[d] (ms)
12 $M_\odot$	1.38	1.26	5.2	2.3	15
15 $M_\odot$	1.47	1.33	7.5	2.5	11
20 $M_\odot$	1.71	1.52	14	3.4	7.0
25 $M_\odot$	1.88	1.66	17	4.1	6.3
35 $M_\odot$ [e]	2.30	1.97	41	6.0	3.0

magnetar progenitor?

[a] Assuming a constant radius of 12 km and a moment of inertia $0.35 M R^2$ (Lattimer & Prakash 2001)

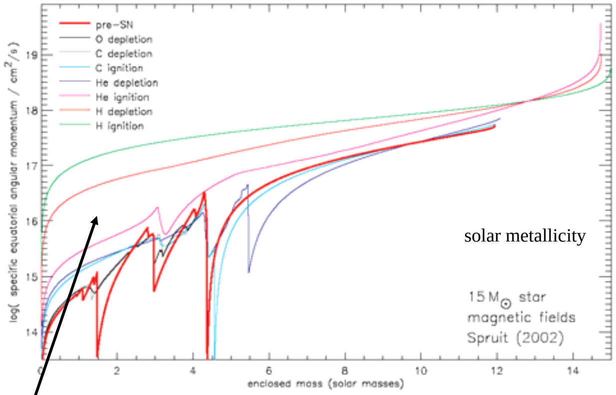
[b] Mass before collapse where specific entropy is 4 k_B/baryon

[c] Mass corrected for neutrino losses

[d] Not corrected for angular momentum carried away by neutrinos

[e] Becaame a Wolf-Rayet star during helium burning

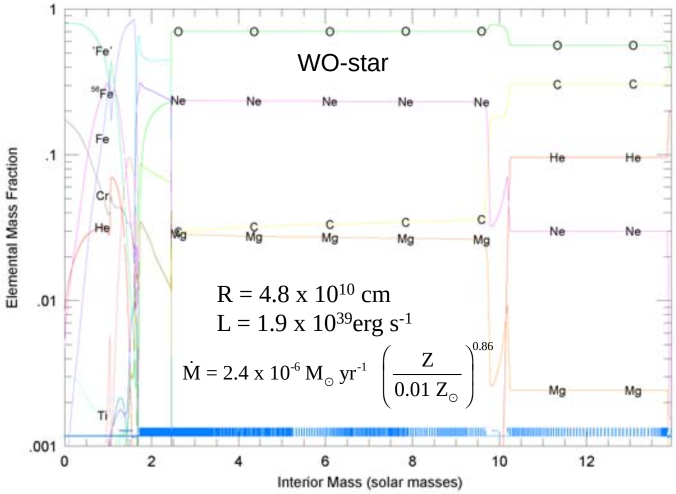
Heger, Woosley, & Spruit (2004) using magnetic torques as derived in Spruit (2002)



solar metallicity

Much of the spin down occurs as the star evolves from H depletion to He ignition, i.e. forming a red supergiant.

Heger, Woosley, & Spruit (2004)

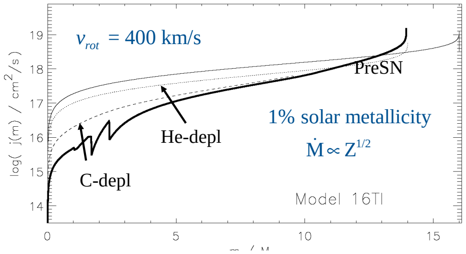


$R = 4.8 \times 10^{10}$ cm

$L = 1.9 \times 10^{39}$ erg s^{-1}

$$\dot{M} = 2.4 \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1} \left(\frac{Z}{0.01\ Z_\odot}\right)^{0.86}$$

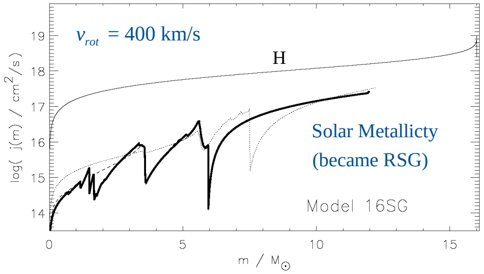
Derived from 16 $M_\odot$ star with rapid rotation



1% solar metallicity

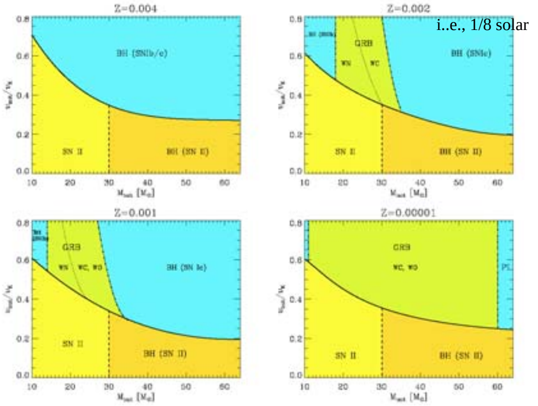
$\dot{M} \propto Z^{1/2}$

GRB



Solar Metallicty (became RSG)

8 ms pulsar

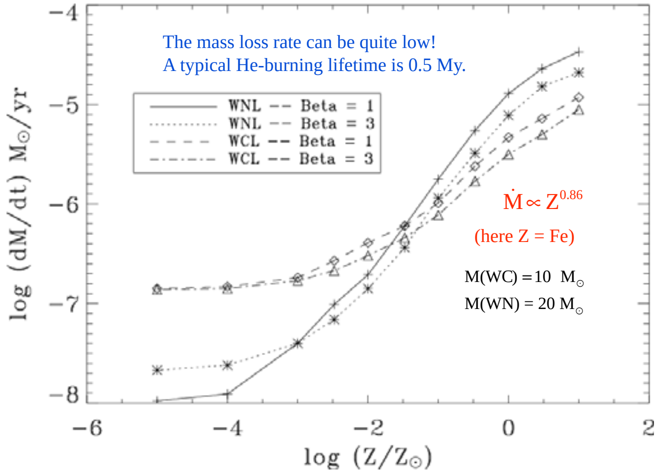


i..e., 1/8 solar

Yoon, Langer,
and Norman (2006)

$N_{GRB} / N_{SN} \ll 1\%$
out to redshift 4
saturates at 2% at
redshift 10

Woosley and Heger (2006) find similar results but estimate a higher metallicity threshold (30% solar) and a higher mass cut off for making GRBs.



The mass loss rate can be quite low!
A typical He-burning lifetime is 0.5 My.

$\dot{M} \propto Z^{0.86}$

(here Z = Fe)

M(WC) = 10 $M_\odot$
M(WN) = 20 $M_\odot$

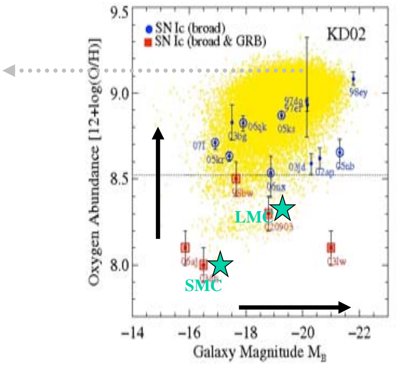
Theory

Vink & de Koter (A&A, 442, 587, (2005))

Savalio et al. (2009, ApJ, 691, 182) surveyed 46 GRB host galaxies. Found median mass to be $10^{9.3}$ solar masses (like the LMC) and the metallicity, 1/6 solar. SHBs seem (small statistics) to be in larger galaxies.

Local abundances of GRB-SN and broad-lined SN Ic

Local SDSS
galaxies
(Tremonti et al
2004)



Modjaz et al (2008)

Additional Predictions Collapsar Model

- Have a time scale governed by the dynamics of the star and accretion, i.e., not a pulsar spin down time
- Separate mechanism for SN and GRB
- At higher redshift (lower metallicity) LSBs should, in general have more total energy and last longer
- Total explosion energies can considerably exceed 2 x 10^{52} erg (difficult in magnetar model)
- Substantial late time activity due to fallback (Type II collapsar)
- New kinds of phenomena at very high mass (Type III collapsar)

Short Hard Bursts

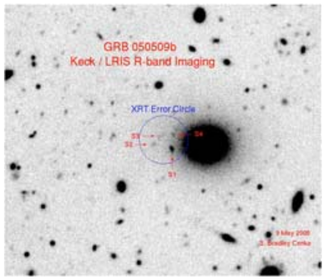
In 2005 - 2006, several short hard bursts were localized by SWIFT and HETE-2 and coordinated searches for counterparts were carried out. The bursts were GRB 050509b (z = 0.2248, elliptical galaxy), 050709 (z = 0.161) and 050724 (z = 0.258)

The bursts were either on the outskirts of galaxies or in old galaxies with low star formation rate

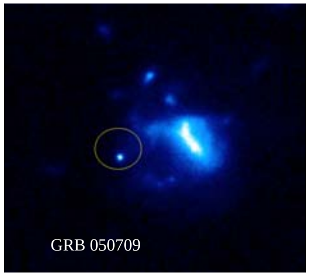
There was no accompanying supernova

The redshifts were much lower than for the long soft bursts and thus the total energy was about two orders of magnitude less (because they are shorter as well as closer).

All this is consistent with the merging neutron star (or merging black hole neutron star) paradigm.

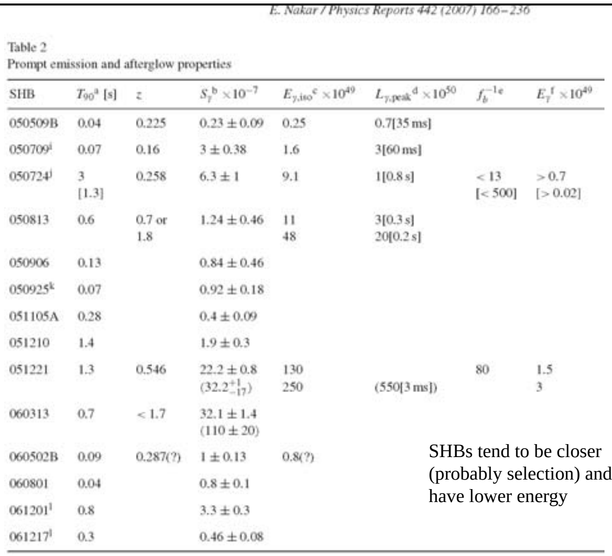


near an elliptical



outskirts of an Ir galaxy

Spectrum of 050724 host galaxy shows it to be an elliptical

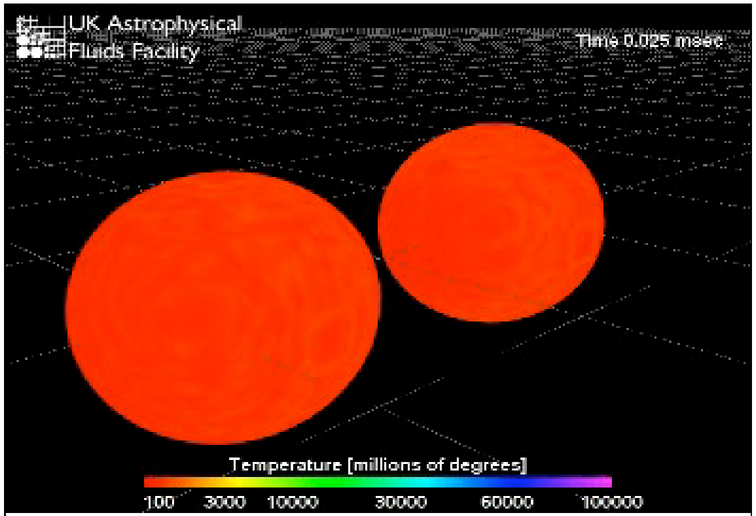


E. Nakar / Physics Reports 442 (2007) 166–236

Table 2
Prompt emission and afterglow properties

SHB	T_{90}[a] [s]	z	S_γ[b] $\times 10^{-7}$	$E_{\gamma,\mathrm{iso}}$[c] $\times 10^{49}$	$L_{\gamma,\mathrm{peak}}$[d] $\times 10^{50}$	f_b^{-1}[e]	E_γ[f] $\times 10^{49}$
050509B	0.04	0.225	0.23 ± 0.09	0.25	0.7[35 ms]		
050709[i]	0.07	0.16	3 ± 0.38	1.6	3[60 ms]		
050724[j]	3 [1.3]	0.258	6.3 ± 1	9.1	1[0.8 s]	< 13 $[< 500]$	> 0.7 $[> 0.02]$
050813	0.6	0.7 or 1.8	1.24 ± 0.46	11 48	3[0.3 s] 20[0.2 s]		
050906	0.13		0.84 ± 0.46				
050925[k]	0.07		0.92 ± 0.18				
051105A	0.28		0.4 ± 0.09				
051210	1.4		1.9 ± 0.3				
051221	1.3	0.546	22.2 ± 0.8 (32.2^{+1}_{-17})	130 250	(550[3 ms])	80	1.5 3
060313	0.7	< 1.7	32.1 ± 1.4 (110 ± 20)				
060502B	0.09	0.287(?)	1 ± 0.13	0.8(?)			
060801	0.04		0.8 ± 0.1				
061201[l]	0.8		3.3 ± 0.3				
061217[l]	0.3		0.46 ± 0.08				

SHBs tend to be closer (probably selection) and have lower energy



Rosswog (2003)