Gamma Ray Bursts

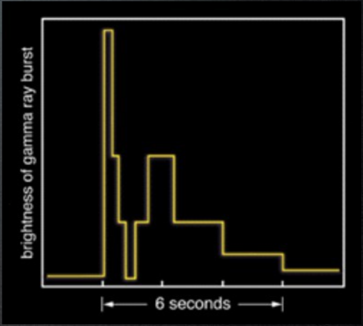
- Definition
- History
- Classification
- Energetics
- Progenitors
- Rates
- Threats

Discovery

The Vela Satellites:

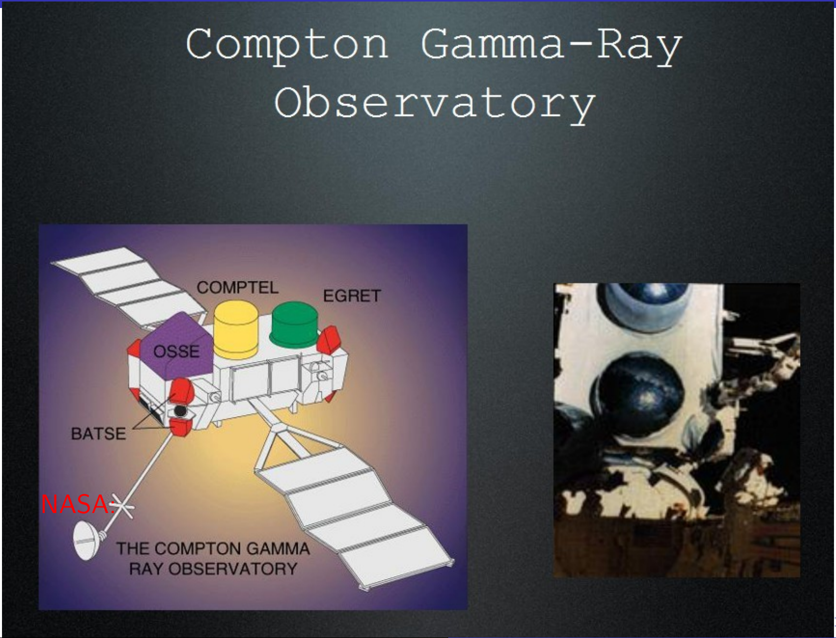
Protecting the Free World from Illicit GRBs

NASA:



Designed to detect nuclear tests (in violation of the test ban treaty), the Vela satellites discovered GRBs

Follow-Up


Compton Gamma-Ray Observatory
COMPTEL
EGRET
OSSE
BATSE
NASA:
THE COMPTON GAMMA RAY OBSERVATORY

Gamma Ray Bursts

- Flashes of gamma rays associated with energetic explosions in distant galaxies.
- Believed to be most luminous electromagnetic events since the Big Bang.
- Observed fluxes are hundreds of times brighter than supernovae, although seem to be highly beamed, so that total luminosity is comparable to that of a supernova.
- Bursts last from milliseconds to tens of seconds and show great variety.
- Often followed by an afterglow in longer wavelengths up to radio, in some cases resembling the light curve from a supernova.
- Thought to originate in some supernovae and mergers of binary compact objects.
- Isotropic distribution shows they are at cosmological distances.
- Observed frequency is about 1 per day; actual rate due to beaming is much greater.

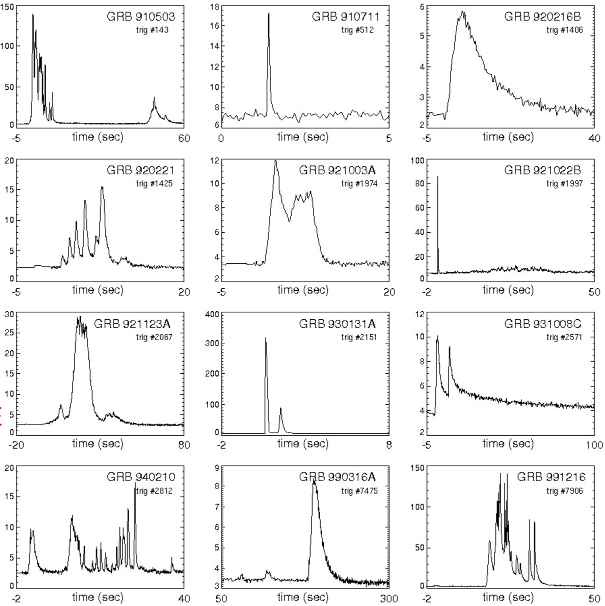
Despite funding cuts, research into the origin of gamma-ray bursts continues as best it can.

Gamma Ray Burst Light Curves

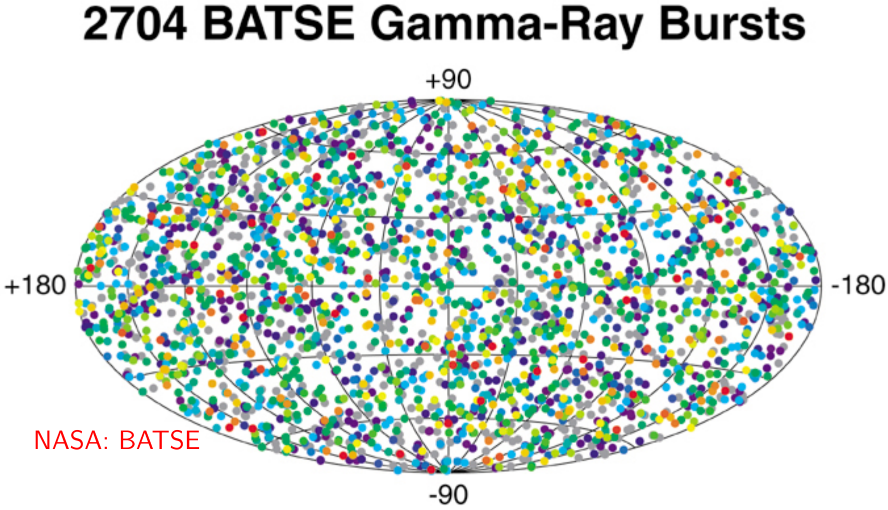
None are identical:

- duration
- # of peaks
- symmetry
- precursors

NASA: BATSE



Gamma Ray Burst Distribution

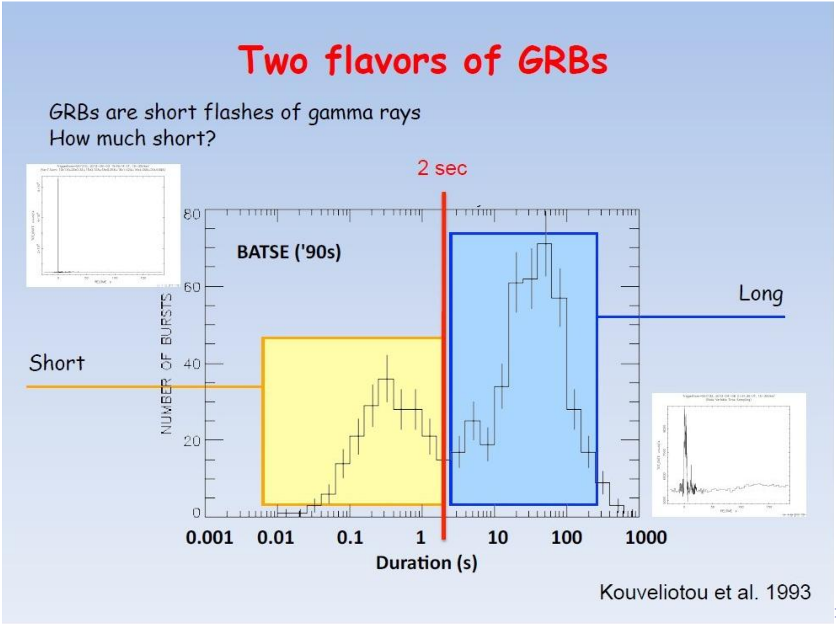


NASA: BATSE

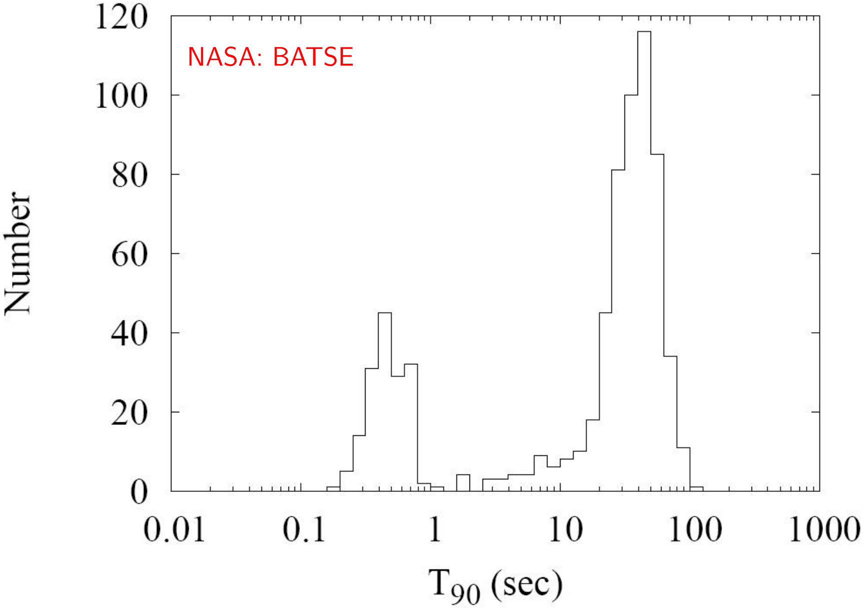
Discovery of Gamma Ray Bursts

- First observed in 1967 by U.S. Vela 3 and 4 satellites launched in conjunction with Nuclear Test Ban Treaty
- Signature unlike a nuclear weapon, but observations were classified
- Continued observations of bursts continued, and solar and terrestrial origins ruled out
- Observations declassified in 1973
- Controversy concerning locations of bursts: Milky Way or cosmological? settled only after launch in 1991 of the Compton Gamma Ray Observatory containing the Burst and Transient Source Explorer (BATSE), which showed isotropic, and therefore cosmological, distribution
- For decades, searches were made to identify counterparts in other spectral regimes without success
- Breakthrough reached in 1997 with satellite BeppoSAX detected the burst GRB 970228
- X-ray camera detected fading X-ray emission and optical observations found a fading optical counterpart. Deep imaging revealed a faint host galaxy at this location. Dimness of galaxy did not allow a redshift measurement at the time.
- A second GRB detected by BeppoSAX, GRB 970508, was identified in optical only 4 hours after its discovery. Redshift of $z = 0.835$ measured ($D = 6$ billion lt. yr.)

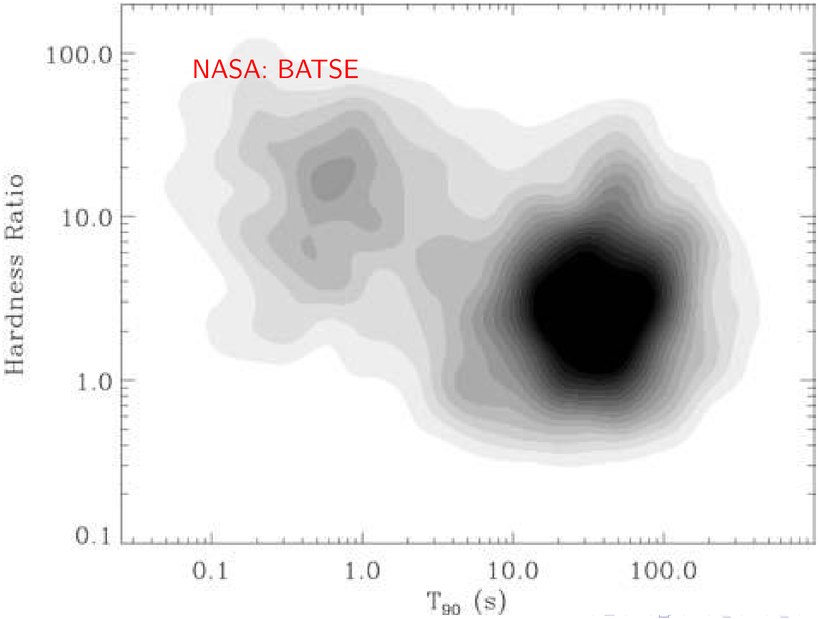
Two Kinds


Two flavors of GRBs
GRBs are short flashes of gamma rays
How much short?
2 sec
BATSE ('90s)
Long
Short
NUMBER OF BURSTS
0
20
40
60
80
0.001
0.01
0.1
1
10
100
1000
Duration (s)
Kouveliotou et al. 1993

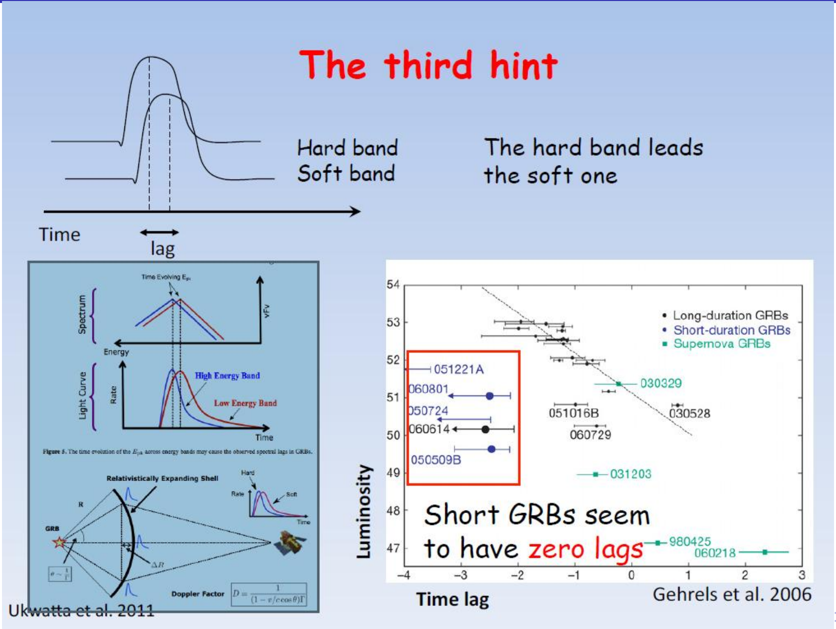
Bimodality of Gamma Ray Bursts



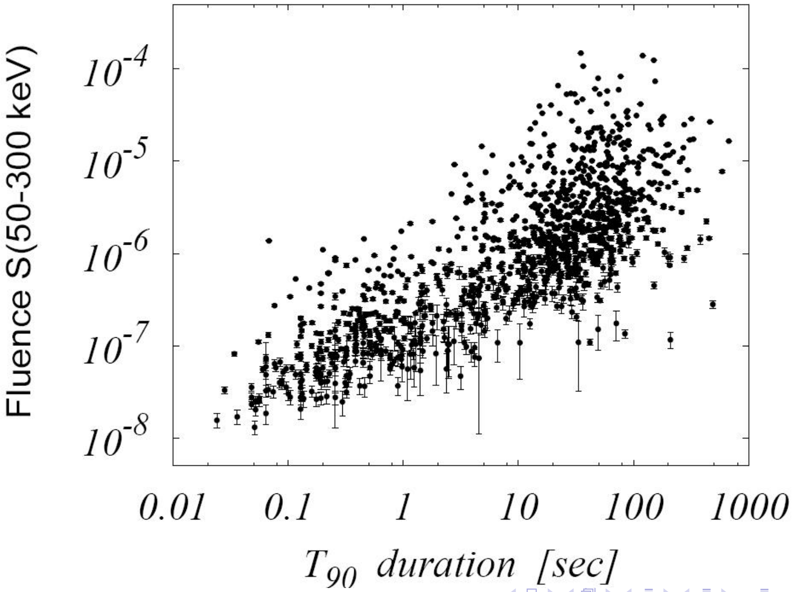
Bimodality of Gamma Ray Bursts



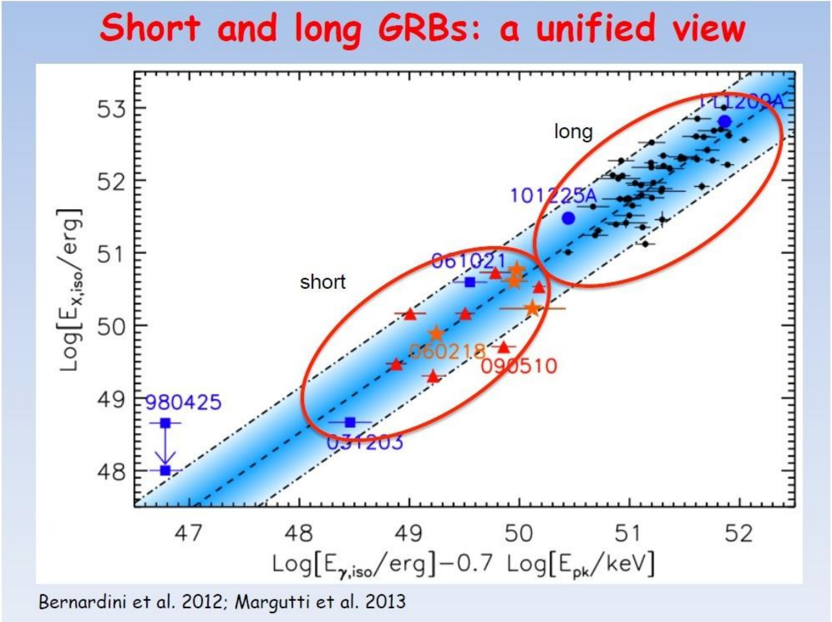
Two Kinds


The third hint
Hard band
Soft band
The hard band leads
the soft one
Time
lag
Time Evolving E_{pk}
Spectrum
Energy
vFv
Light Curve
Rate
High Energy Band
Low Energy Band
Time
Figure 5. The time evolution of the E_{pk} across energy bands may cause the observed spectral lags in GRBs.
Relativistically Expanding Shell
R
GRB
ΔR
Hard
Rate
Soft
Time
Doppler Factor
$D = \frac{1}{(1 - v/c\cos\theta)\Gamma}$
Ukwatta et al. 2011
Luminosity
Time lag
Long-duration GRBs
Short-duration GRBs
Supernova GRBs
051221A
060801
050724
060614
050509B
030329
051016B
030528
060729
031203
980425
060218
Short GRBs seem
to have zero lags
Gehrels et al. 2006

Fluence of Gamma Ray Bursts



Unified View



Distances to Gamma Ray Bursts

A source emitting energy E at distance d would give an integrated flux (fluence) S

$$S = \frac{E}{4\pi d^2}.$$

If $d = 100$ AU (comets), $E \sim 10^{27}$ erg
$d = 1$ kpc (neutron star), $E \sim 10^{40}$ erg
$d = 1$ Gpc (galaxies), $E \sim 10^{52}$ erg.
All sources with $S > S_{min}$ are detected out to a maximum distance

$$d_{max} = \sqrt{\frac{E}{4\pi S_{min}}}.$$

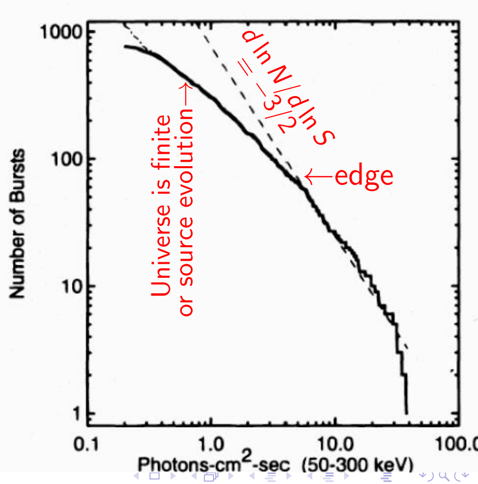
The volume with sources having $S > S_{min}$ is

$$V = \frac{4\pi}{3} d_{max}^3.$$

Distribution is isotropic, the 'edge' is cosmological, not galactic.

If n is the source number density, the number in volume V is

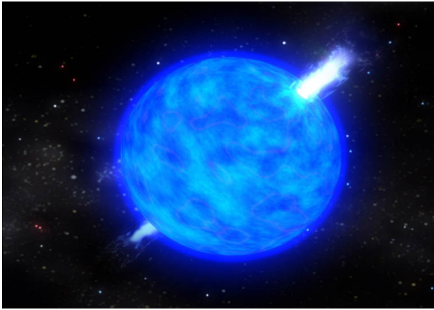
$$N = nV = \frac{4\pi}{3} n \left(\frac{E}{4\pi S_{min}}\right)^{3/2} \propto S_{min}^{-3/2}.$$



Energetics of Gamma Ray Bursters

The energy output of GRB 080319B, if spherically radiated, is $> 10^{54}$ erg. This exceeds any reasonable source during such a short timescale, so the radiation is likely highly beamed.

A black hole forms at the center of the GRB source. It is rapidly rotating and almost certainly has a large magnetic field. It creates a fireball of relativistic electrons, positrons and photons which expands and collides with stellar material and creates gamma rays which emerge from the star in beams ahead of the blast wave.



Additional emissions, or afterglow, are created by collisions of the shock (and a reverse shock) with intervening matter. We can see both the jet and the afterglow if the beam is directed towards us.

Beaming of Gamma Ray Bursters

The degree of beaming can be estimated by observing 'jet breaks' in the afterglow light curves, a time after which the afterglow fades rapidly as the jet slows down. Observations suggest jet angles from 2 to 20 degrees. The jet accelerates a thin shell, which decelerates as it expands in a time

$$t_\gamma = \frac{R_\gamma}{2\gamma_0^2 c} = \left(\frac{3E}{32\pi\gamma_0^8 n m_p c^5}\right)^{1/3}.$$

R_γ is the shell radius, $\gamma_0 = (1 - v^2/c^2)^{-1/2}$ is the relativity parameter, n is the density and E is the total energy.

The jet break time t_{jb} can then be connected to the relativity parameter

$$\gamma_0 = \left(\frac{3E}{32\pi n m_p c^5 t_{jb}^3}\right)^{1/8} \simeq 320\left(\frac{E_{51}}{n_1 t_{jb,10}^3}\right)^{1/8}.$$

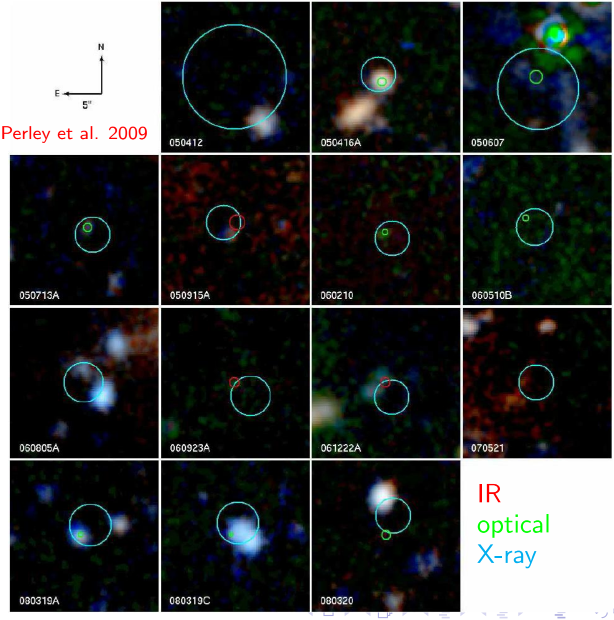
A relativistic jet has an opening or beaming angle $\theta_0 \simeq \gamma_0^{-1}$.

Dark GRBs

Some GRBs have bright X-ray but only extremely weak optical afterglows.

This is due to dust obscuration within the host galaxy.

Perley et al. 2009



GRBs As Probes of Chemical Evolution

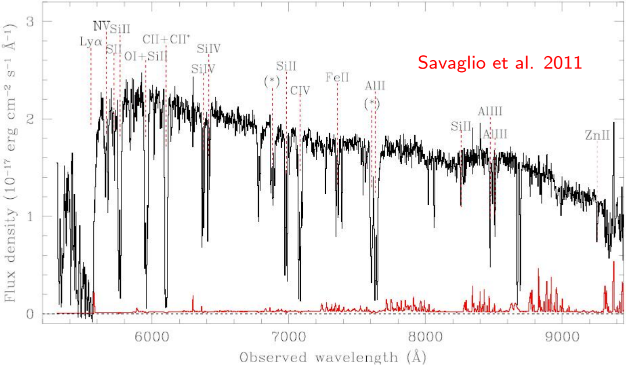
GRB light is absorbed by intervening galaxies.

Two systems, $z = 3.5673$ and $z = 3.5774$, probably merging galaxies, are illuminated.

The progenitor of the GRB could have formed in star formation triggered by galaxy merger.

$[Zn/H] = 0.29$ and $[S/H] = 0.67$ are highest metallicies recorded for $z > 3$ objects.

Shows star formation and metallicities heightened by interaction of galaxies.



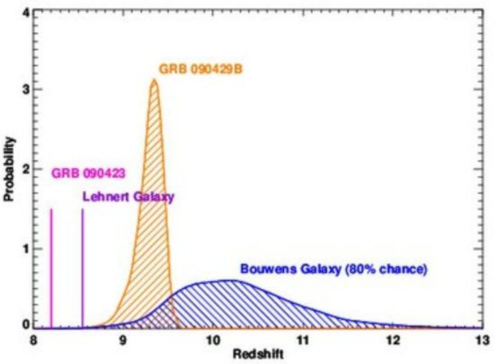
Most Distant GRBs

$z = 8.26$

$t = 630$ Myr

$z = 10$

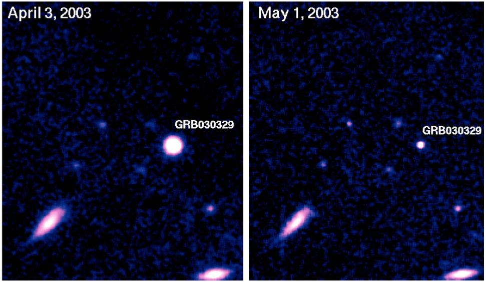
$t = 480$ Myr



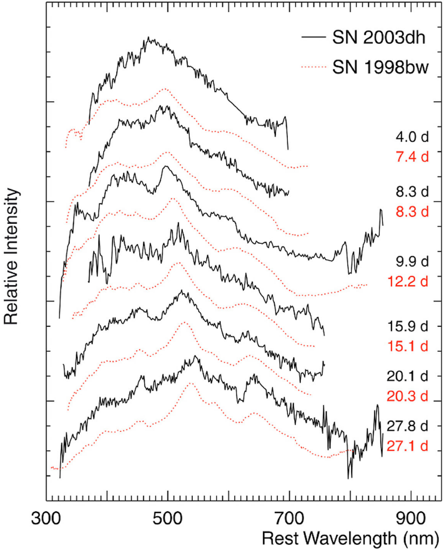
Long Gamma Ray Burst Progenitor

- GRB 980425 was followed within a day by SN 1998bw (type Ib) at the same location, providing the first clues about progenitors.
- BATSE ended in 2000 and was followed by HETE-2 from 200-2007
- Swift launched in 2004 and still operating; this also contains X-ray and optical telescopes for rapid deployment to search for counterparts.
- Fermi Gamma-ray Large Area Telescope (GLAST) launched in 2008 and now detects several hundred bursts per year

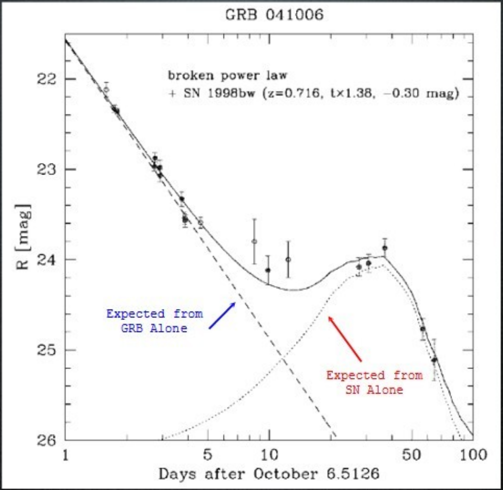
Long GRB Is a Hypernova



ESO

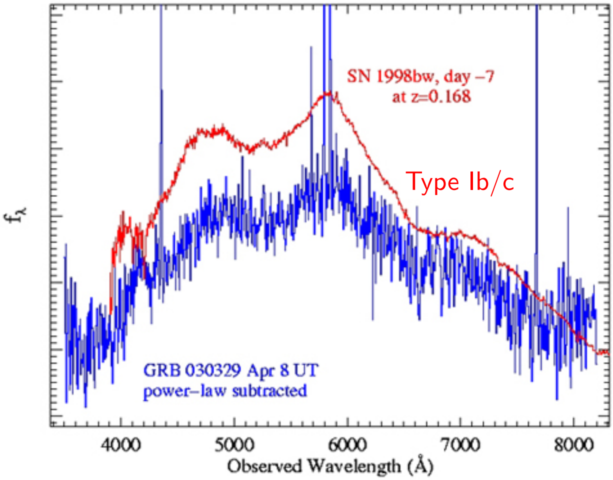


GRBs Go Bump in the Night

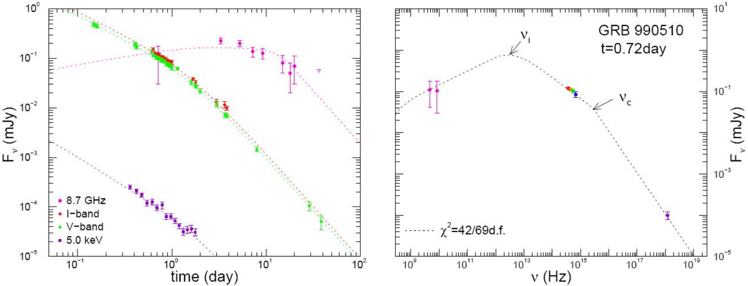


GRBs and Supernovae

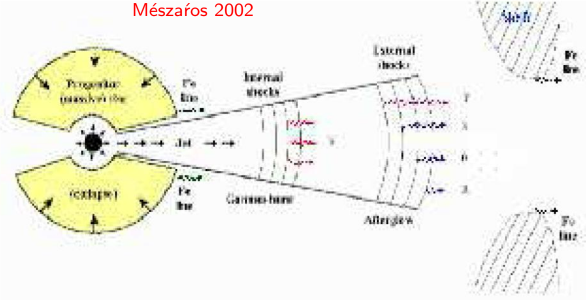
Della Valle et al. 2003



Collapsar Model



Mészáros 2002



GRBs and Progenitors

Almost every long GRB has been associated with a galaxy with rapid star formation, and some long GRBs are linked to supernovae.
The evidence favors that the parent SN population of GRBs are hypernovae, or Type Ib/c SNe from massive progenitors characterized by high luminosity, high expansion veclocites and no H/He in spectra.
The brightest SNe are associated with relatively faint GRBs.

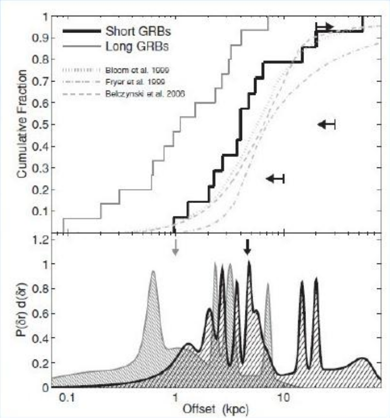
Short GRBs account for about 30% of total, and not until 2005 were their origins clarified. Several short GRB afterglows have been assoicated with large elliptical galaxies or centers of large clusters, both regions of little or no star formation. They are more offset from galactic centers.

Short GRBs have no supernova link, and must be physically distinct from long GRBs. The most prevalent suggestion is that short GRBs are formed in mergers of neutron stars or black holes and neutron stars. Afterglows of minutes to hours in X-rays are consistent with fragments of tidally-disrupted neutron star material (r-process radiation).

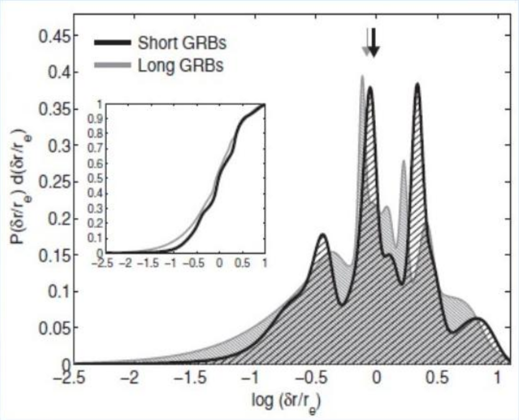
A fraction of low-luminosity short GRBs may be giant flares from soft gamma ray repeaters (magnetized neutron stars) in nearby galaxies.

Short GRBs: Offsets

Offset from HG centre

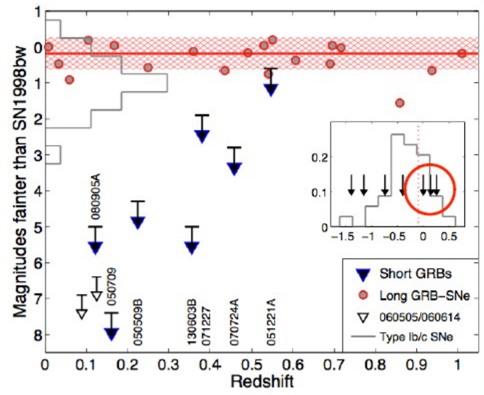


Offset normalized to HG eff. radius

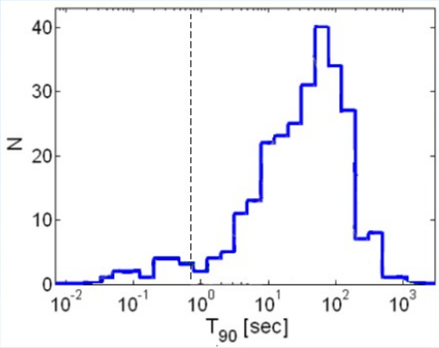


Fong et al. 2010

Short GRBs & (no) SNe



Berger et al. 2014

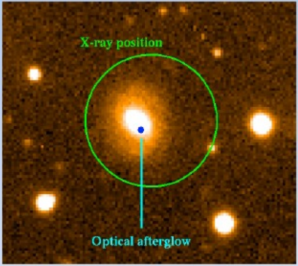


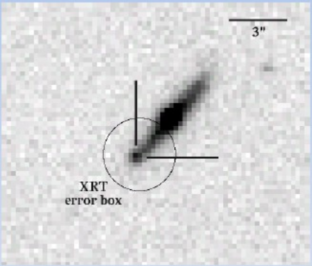
Bromberg et al. 2012

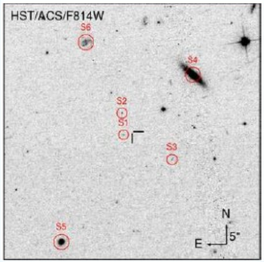
At least 3 short GRB with duration > 1 s
have no SN associated

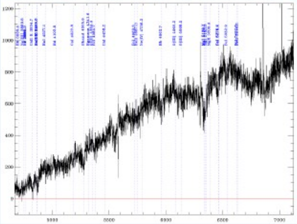
Short GRB hosts

Early-type	Late-type	Host-less









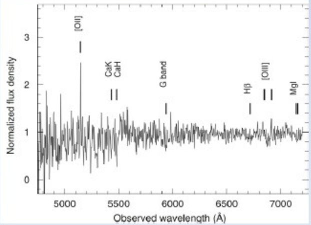


TABLE 2
OBSERVATIONS OF SHORT GRBS WITH OPTICAL AFTERGLOWS AND NO COINCIDENT HOST GALAXIES
(*Sample 2*)

GRB	Instrument	Filter	t_{exp} (s)	m_{lim} [a] (AB mag)
061201	HST/ACS	F814W	2224	26.0
070809	Magellan/LDSS3	*r*	1500	25.4
080503	HST/WFPC2	F606W	4000	25.7
090305	Magellan/LDSS3	*r*	2400	25.6
090515	Gemini-N/GMOS	*r*	1800	26.5

NOTE. — [a] Limits are 3σ.

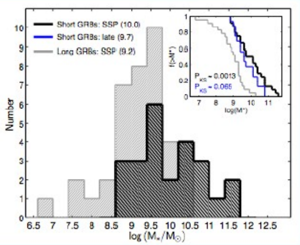
GRB 050724
Barthelmy et al. 2005;
Malesani et al. 2007

GRB 071227
D'Avanzo et al. 2009

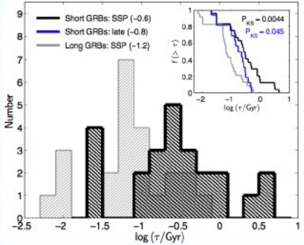
- High-z?
- (very-)low lum HG?
- kicked progenitor?

Short GRB host galaxies

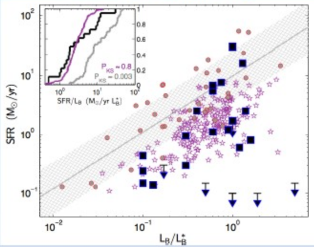
Mass



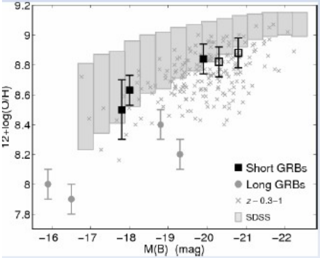
Age



SFR & Luminosity



Metallicity

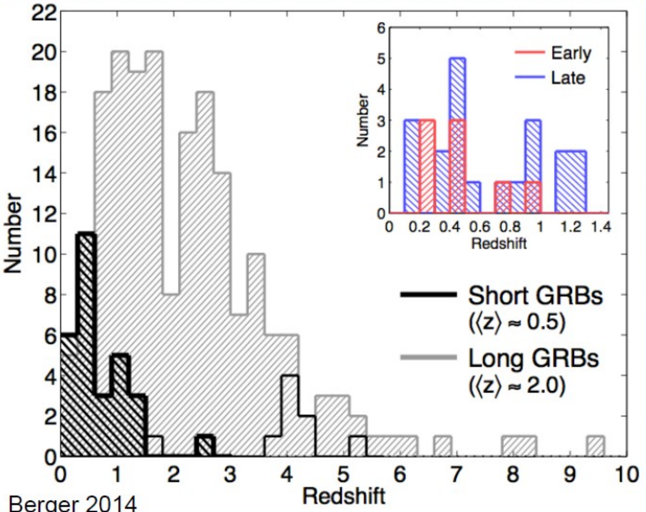


SGRBs are found in all type of galaxies
Properties similar to field (survey) galaxies

LGRBs are found in more peculiar hosts (with respect to field galaxies) mainly in terms of mass, SFR and metallicity

Berger 2009
Berger 2014

Short GRB redshift distribution



Berger 2014

However:
<z> ~ 0.72

If considering *Swift* SGRBs (only) with $T_{90} < 2$ s

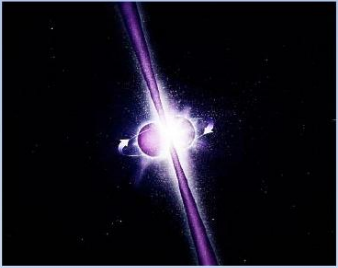
Rowlinson et al. 2013

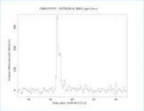
and:
<z> ~ 0.85

for a complete (flux-limited) sample of bright SGRBs (D'Avanzo et al. in prep.)

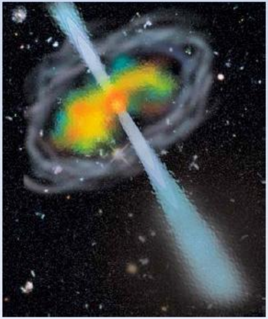
Hinting for a "primordial binary" progenitor, expected to have a z distribution peaking at z ≥ 0.8. (Salvaterra et al. 2008).

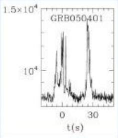
Progenitors





Short/hard GRBs
- no spectral lag
- in all type of galaxies (or no host galaxy at all)
- older stellar population
- no associated SN
- merger progenitor model (and/or magnetars?)

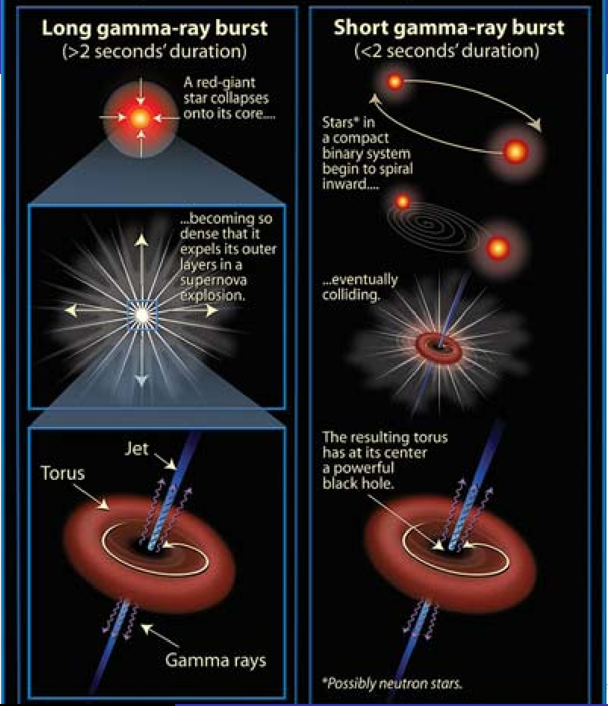




Long/soft GRBs
- spectral lag
- in SF galaxies
- younger stellar population
- many with associated SN
- collapsar progenitor model

GRB Models

The Encylopedia of Science

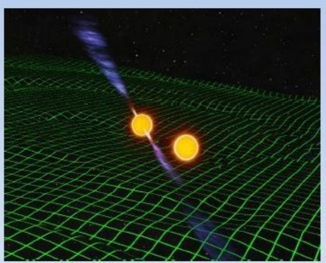


The progenitors of short GRBs

Most popular model:

Coalescence (merging) of a compact object binary system (NS-NS ; NS-BH)

While orbiting, the two objects emit gravitational waves losing energy: MERGING



- critical parameter: **merging time** t_m

Time between the formation of the system and its coalescence

$t_m \propto a^4$ (a: system separation) -> ~10 Myr < t_m < ~10 Gyr

"primordial binaries"

- merging can occur in old and young stellar populations

- **kick velocities**:

Compact objects are the remnants of core-collapse SNe, that can give a "kick"

The system can escape from the HG-> OFFSET! (1÷100 kpc)/low density CBM

(Belczynski & Kalogera 2001; Perna & Belczynski 2002; Belczynski et al. 2006)

Double Neutron Star Mergers

Initial mass transfer

First supernova and kick

Be/X-ray binary

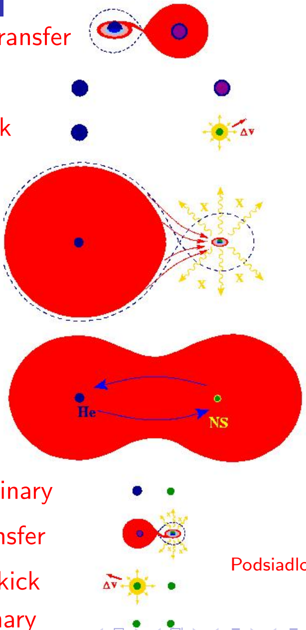
Common-envelope evolution

Helium star–neutron star binary

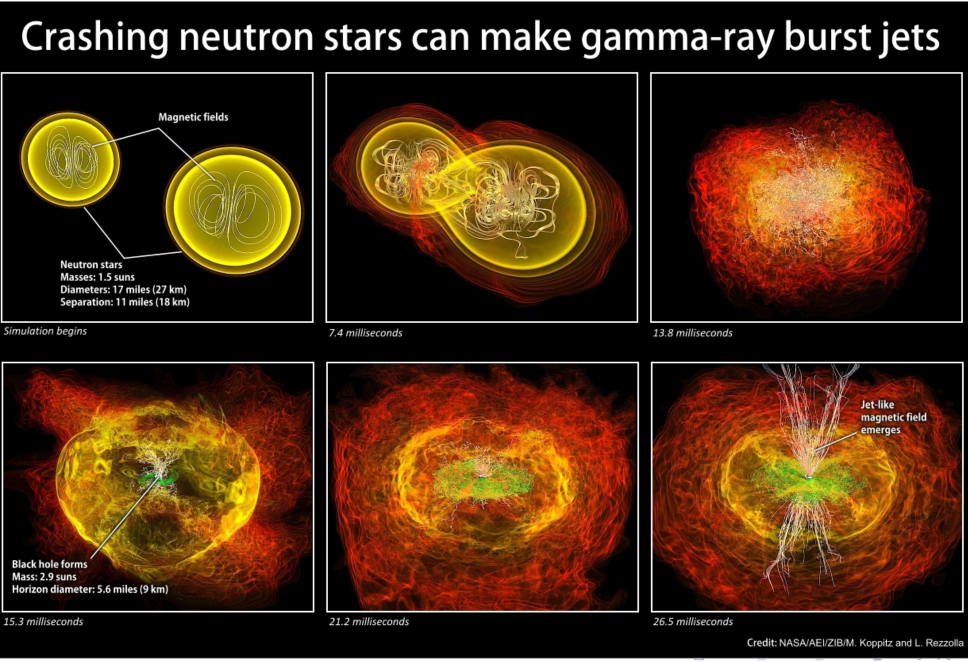
Secondary mass transfer

Second supernova and kick

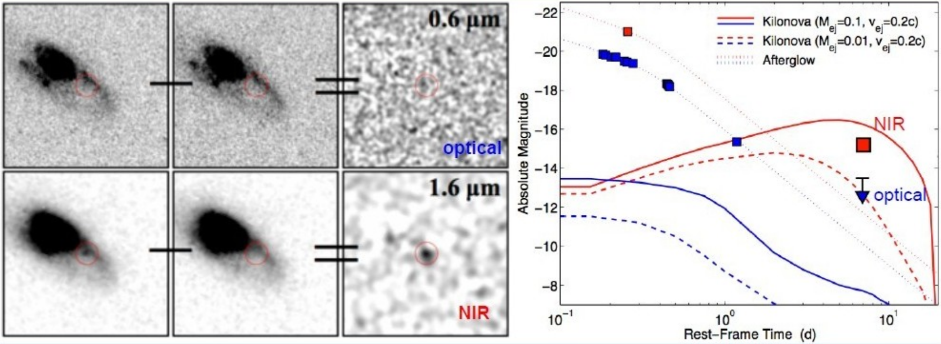
Double neutron star binary



Podsiadlowski


Crashing neutron stars can make gamma-ray burst jets
Magnetic fields
Neutron stars
Masses: 1.5 suns
Diameters: 17 miles (27 km)
Separation: 11 miles (18 km)
Simulation begins
7.4 milliseconds
13.8 milliseconds
Black hole forms
Mass: 2.9 suns
Horizon diameter: 5.6 miles (9 km)
15.3 milliseconds
21.2 milliseconds
Jet-like
magnetic field
emerges
26.5 milliseconds
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

A Kilonova associated to GRB 130603B?

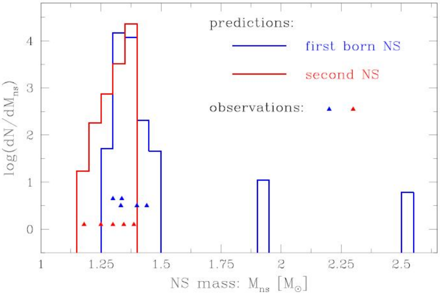


Tanvir et al. 2013

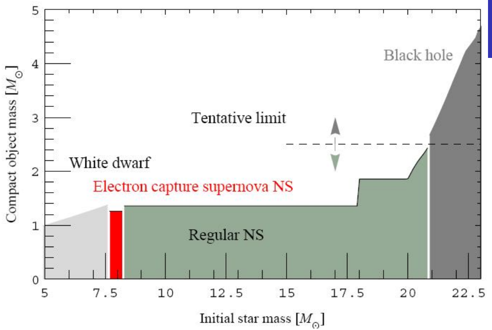
Berger et al. 2013

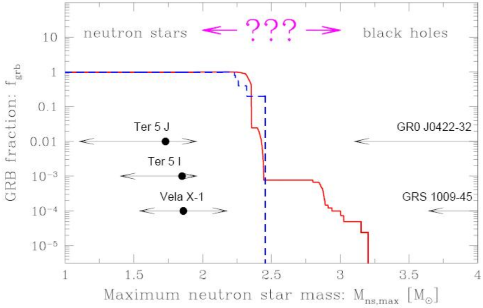
A "flux excess" is seen in the X-ray light curve too. Suggested to be due to fall-back accretion or to magnetar spin-down (Fong et al. 2014)

Mergers–Maximum Mass

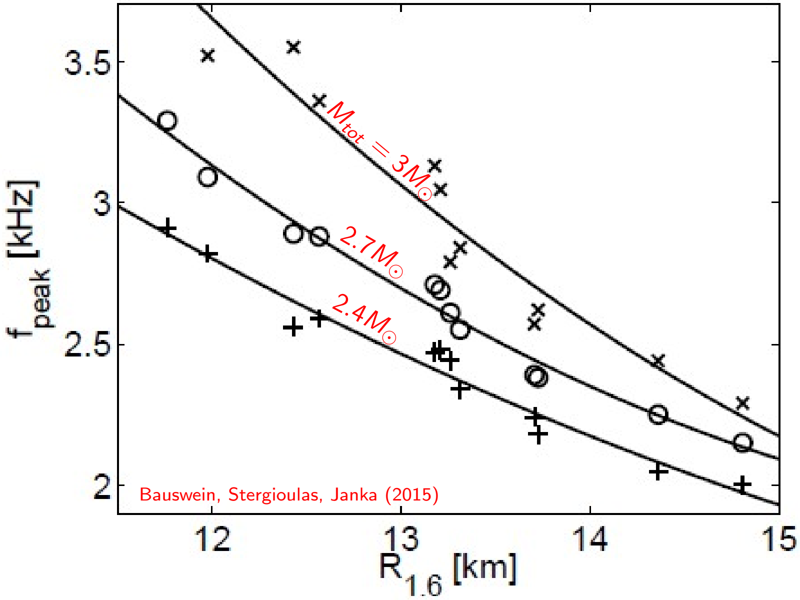


Belczynski et al. 2007





Mergers–Neutron Star Radii



Rates of Gamma Ray Bursters

More than 1 per day is observed, but due to beaming, the actual rate is perhaps 1 per minute in the universe.

Within our galaxy, the rate is estimated to lie between 1 per 100,000 and 1,000,000 years. Less than 10% of these would be beamed in our direction.

It has been suggested that the Ordovician-Silurian extinction, 450 Myrs ago, was caused by a GRB. Evidence is the extinction of tribolites which were upper ocean dwellers. Other species living on land or in shallow seas were also particularly hard hit. Species that were deep-water dwellers were relatively unharmed.

The rate per volume of long GRBs is estimated to be between 100 and 1000 per Gpc^3 per year, which is 1 to 10% of the rate of Type Ib/c supernovae. This difference is probably due to beaming, i.e., $\sim \theta^{-1}$.

Gamma Ray Bursters and the Fermi Paradox

Fermi's Paradox:

The universe is over 10^{10} years old and the galaxy is about $D = 100,000$ lt. yrs. across with about 1 light year between stars on average. An advanced civilization will take about 10,000 years to advance from star to star, traveling with the Earth's orbital velocity, or about 100 years if advanced technologies allow $v = 0.01c$.

There will be a delay between successive colonizations, and colonization would tend to be somewhat random, but the time needed to colonize the galaxy could be as short as $10D/v \sim 10^8$ yrs.

Fermi's Paradox is the mismatch between the Galaxy's age and the colonization timescale.

There is no evidence aliens have ever been nearby. Perhaps gamma ray bursts, causing repeated sterilizations, have prevented intelligence from developing and colonization occurring until now.

A gamma ray burst occurs in our Galaxy every 10^6 years now but the rate was higher in the past. About 1% might be beamed in our direction. Assume each such burst causes an extinction in the beam path. 10^{10} years ago, a spot in the Galaxy could expect an extinction every 10^6 years; now it would be perhaps $1-2\times10^8$ years between extinctions.

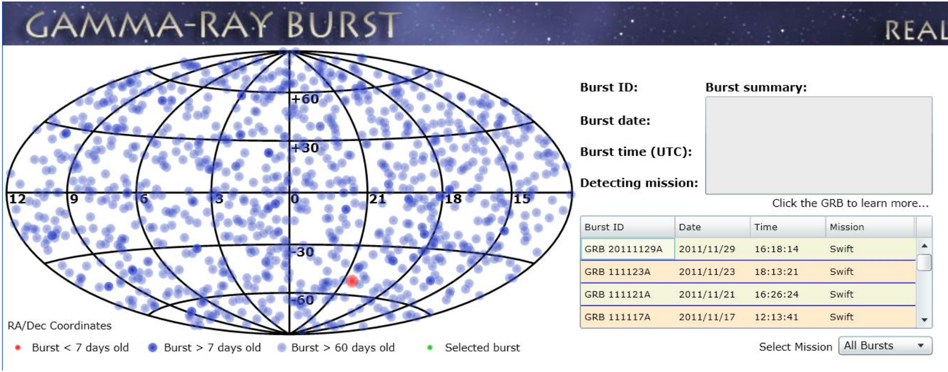
Life in seas might be protected better than life on land; but life on land became prominent only $3-4\times10^8$ years ago. The relevant time is the timescale for the rise of intelligent life, not from single-celled life, but from multicellular life in the oceans. It could take $1-3\times10^8$ years to develop sufficient complexity for intelligence.

The important point is that the two relevant timescales are about the same, $1-2\times10^8$ **yrs.** This should set up an equilibrium.

Once the gamma-ray burst rate decreases below the intelligent evolution rate (both are inversely equal to their respective timescales), intelligent civilizations will begin to develop. It is interesting that the colonization timescale is also the same, so this answers Fermi's question: "They haven't had time to get here yet!"

J. Annis, J. Br. Int. Soc. 52, 19 (1999)

GRB Real-Time Monitor



grb.sedona.edu