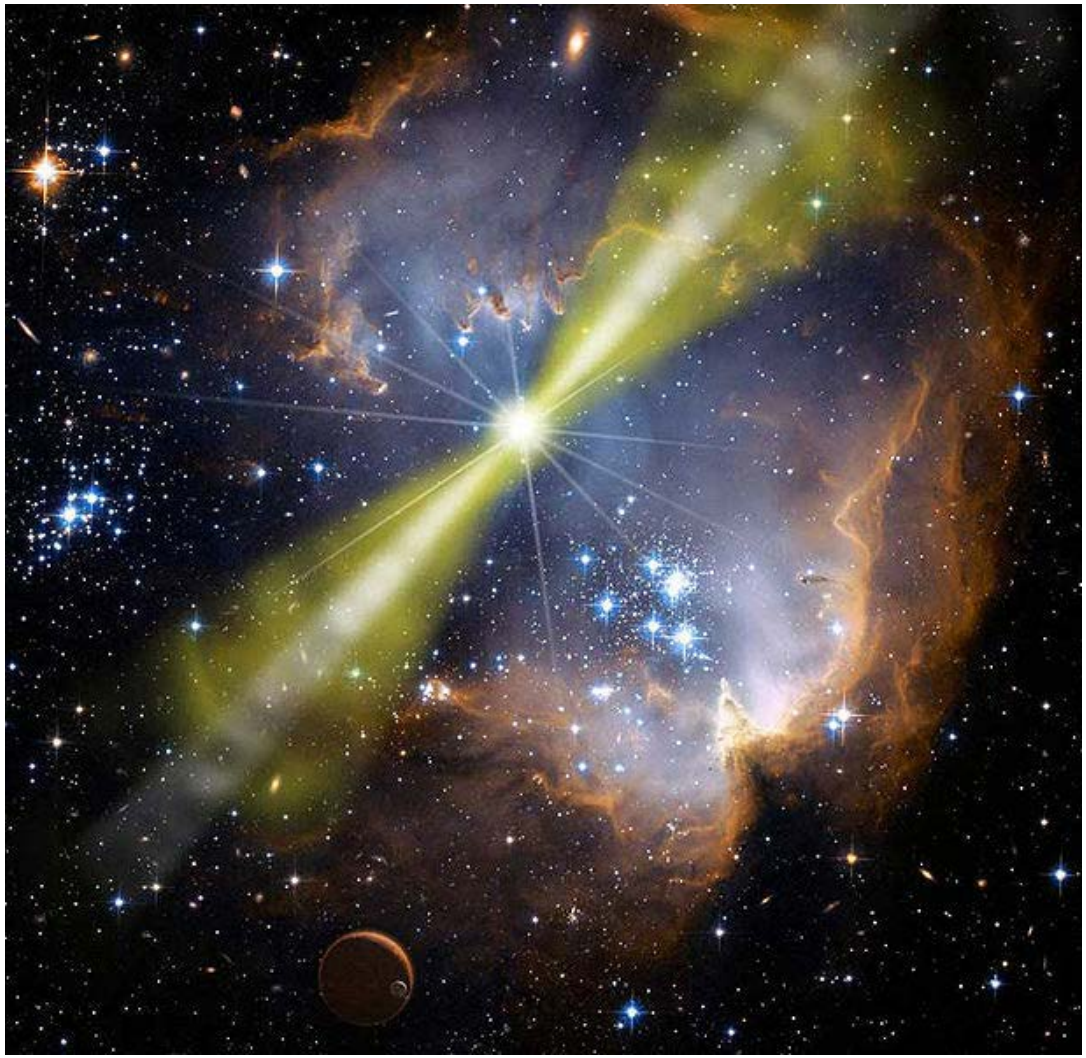
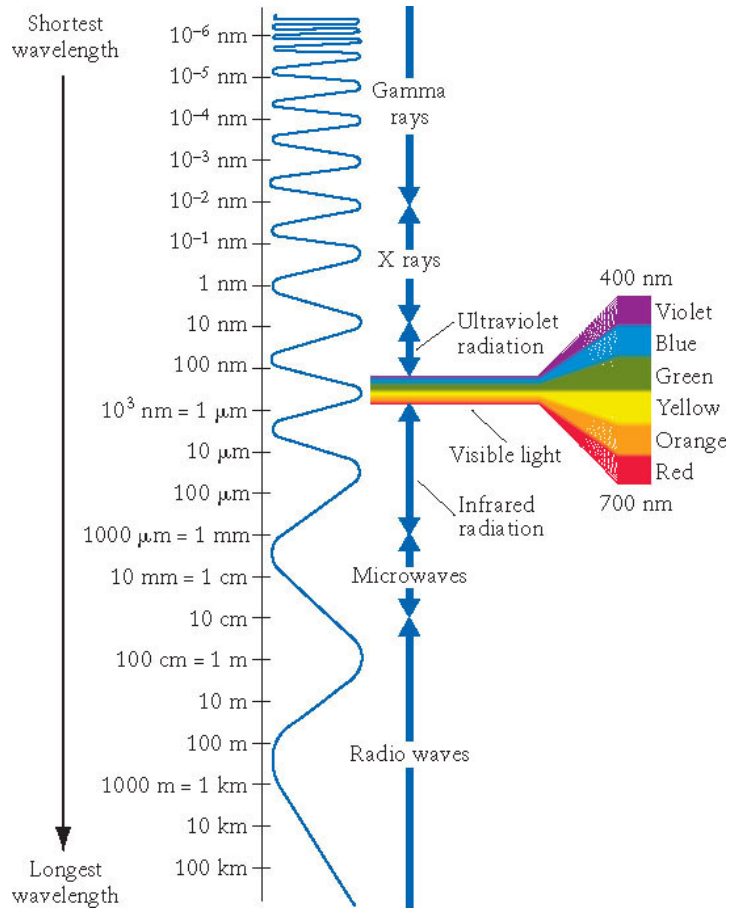
Gamma-Ray Bursts



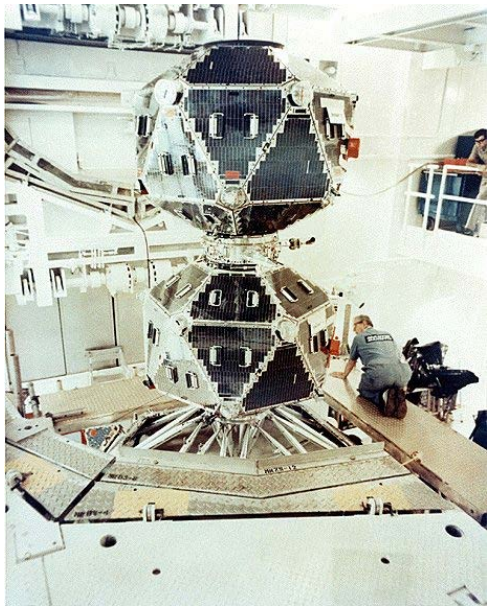
Gamma-Ray Astronomy

Gamma rays are photons with energies > 100 keV and are produced by sub-atomic particle interactions. They are absorbed by our atmosphere making observations from satellites necessary.



Gamma-Ray Bursts

Unexpected Discoveries of the Cold War Era
Gamma-ray bursts were first observed in the late 1960s by the U.S. Vela satellites, which were built to detect gamma radiation pulses emitted by nuclear weapons tested in space.



VELA 5A, 5B

A team at Los Alamos was able to determine rough estimates for the sky positions of several bursts and definitively rule out a terrestrial or solar origin.

The discovery was declassified and published in 1973 as an Astrophysical Journal article entitled "*Observations of Gamma-Ray Bursts of Cosmic Origin*"

Gamma-Ray Bursts

The location of Gamma-Ray Bursts

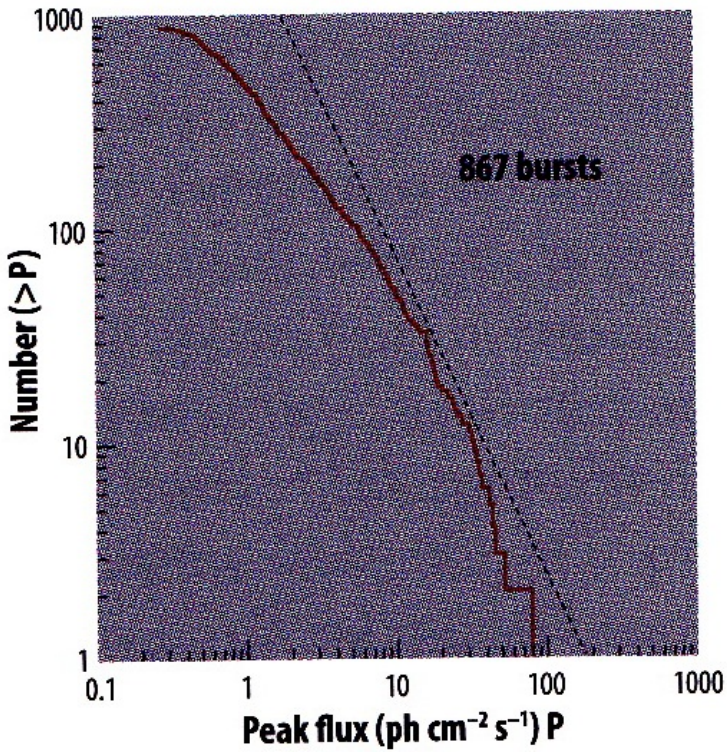
For more than 20 years after their discovery it was debated whether Gamma-ray bursts were produced in our galaxy or originated in other distant galaxies.

The poor positional accuracy of the early detections and their short duration made it difficult to follow up GRBs. Two indirect lines of evidence pointed to a cosmological origin:

a) The cumulative distribution of the peak fluxes of GRBs indicates that they thin out beyond a certain distance.

b) The positions of detected GRBs in the sky.

Gamma-Ray Bursts



Bohdan Paczynski argued for the cosmological origin of GRBs

The plot shows the number of GRBs with a Peak Flux above some given level. If GRBs were uniformly distributed through space one would expect a distribution as shown by the dashed line. There are fewer bursts at faint levels implying they thin out beyond a certain distance.

Gamma-Ray Astronomy

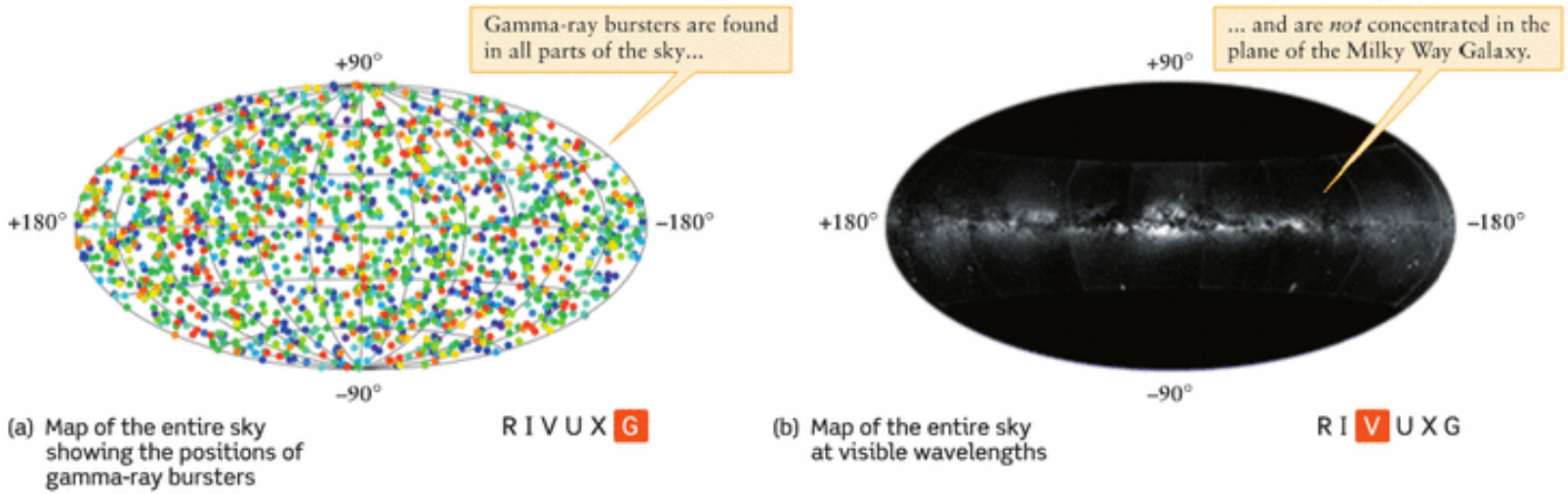
One of the most important gamma-ray telescopes placed in orbit in 1991 was **the Compton Gamma ray Observatory** (**CGRO**).

The **EGRET** instrument conducted the first all sky survey above 100 MeV. Using four years of data it discovered 271 sources.

The Burst and Transient Source Experiment (**BATSE)** instrument (20-600keV) made about 2700 GRB detections.

Instruments on CGRO were **EGRET, BATSE, OSSE, and COMPTEL.**
Energy range (20 keV - 30 GeV).

GRB Distribution

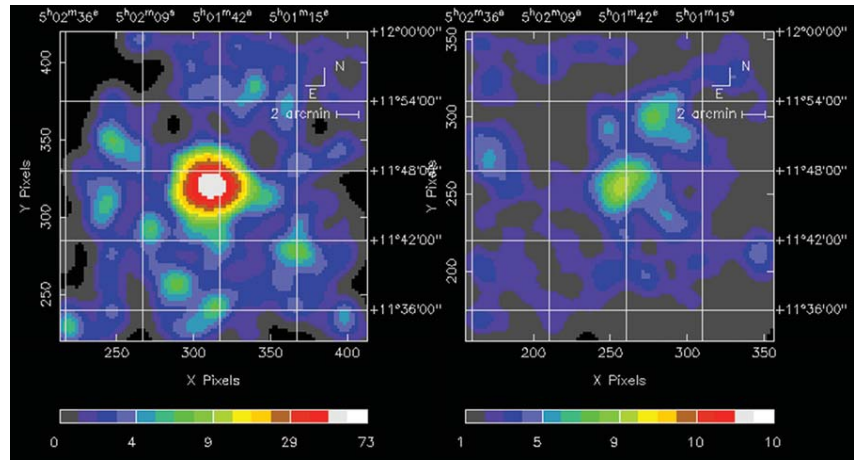


Positions of the 2704 GRBs recorded by the BATSE on the **Compton Gamma-Ray Observatory** are plotted on the sky.

Directions appear to be completely random. This favors the hypothesis that GRBs originate from outside our galaxy and likely from distant galaxies. If GRBs originated from our Galaxy one would have expected an accumulation along the galactic plane or towards the galactic center.

Gamma-Ray Bursts

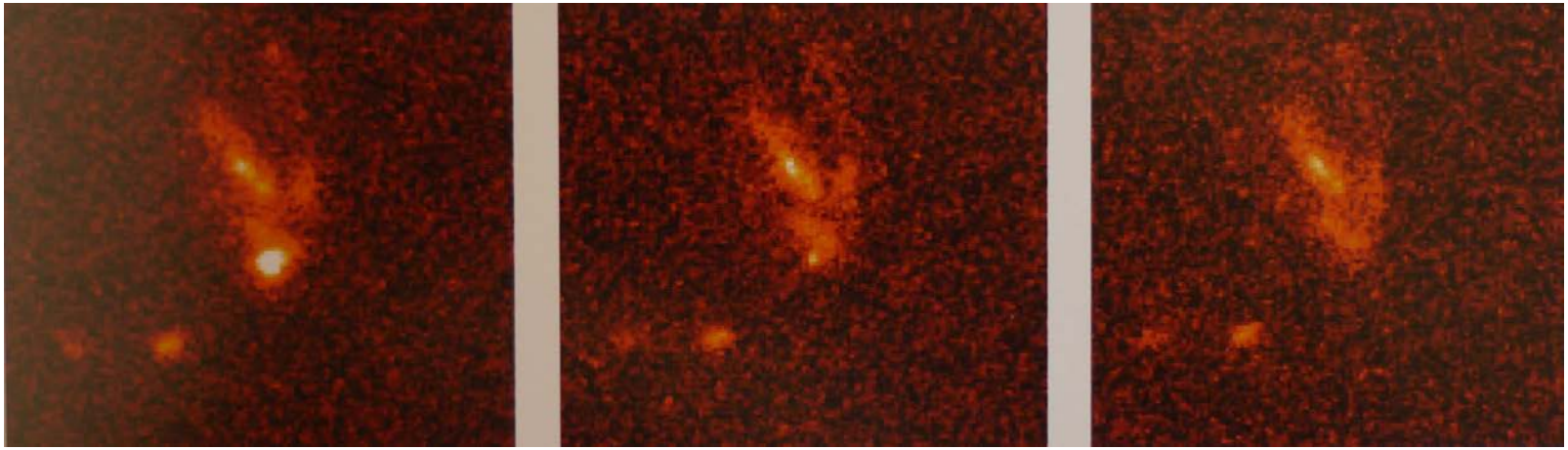
A breakthrough came after the launch of the Gamma-ray and X-ray telescope satellite named **Beppo-SAX**. It combined arcmin resolution and a rapid response.



Beppo-SAX discovered the first GRB afterglow. X-ray images of the afterglow 8 hours (left) and 3 days (right) after the burst.

Astronomers were able to follow up GRBs by taking optical spectra with large optical telescopes such as the 10m Keck in Hawaii. The strong redshifted absorption features confirmed their cosmological origin.

Gamma-Ray Bursts



(a) **(b)** **(c)**

Deep optical observations in the locations where GRBs went off showed that they originate in galaxies.

The ultraluminous GRB 990123 was located on the outskirts of a star-forming galaxy with a redshift of 1.6. The Hubble Space Telescope images show the afterglow at (a)16, (b) 59 and (c) 380 days after the burst.

Models of Gamma-Ray Bursts

Questions:
How are Gamma-Ray bursts produced?

Early measurements indicated that the total energy released during a gamma-ray burst was far more than a supernova's output. Could GRB's arise from some rare type of stellar explosion ("hypernova")?.

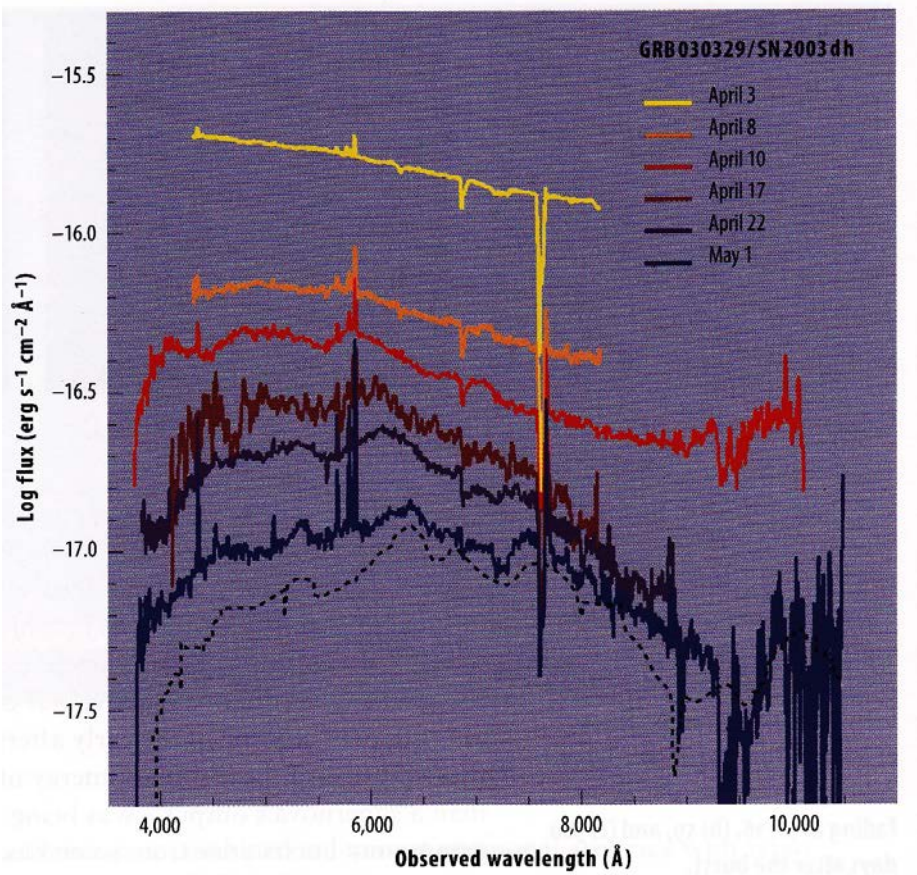
If so how could the energy escape from the stellar envelope of the star within seconds. In regular supernova explosions the stellar envelope slows the release of radiation.

Could the collision of two neutron stars explain the short time-scale of the burst?

Models of Gamma-Ray Bursts

Follow up of several GRBs with optical spectral observations showed spectra that resembled those of supernovae.

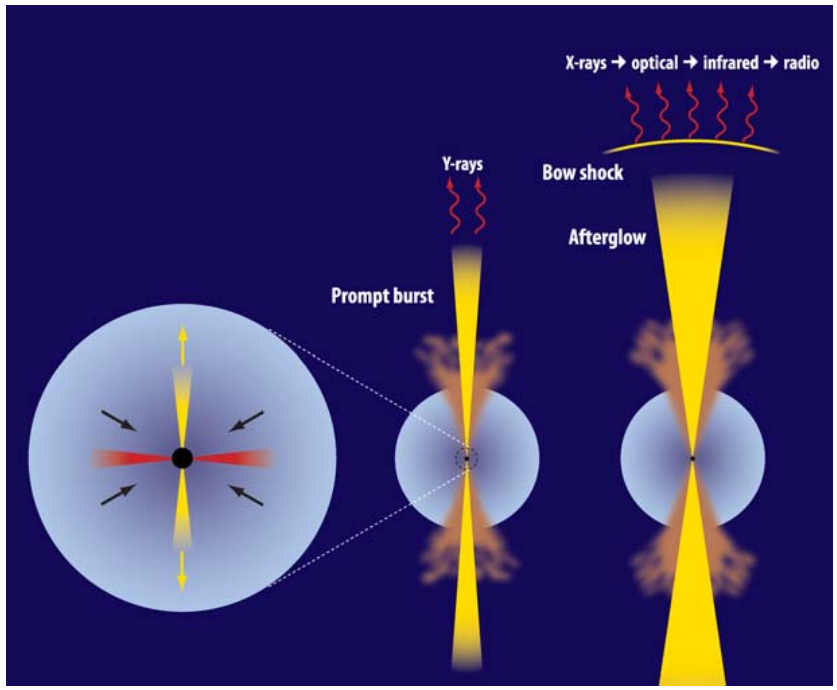
As the optical afterglow of GRB 030329 faded, the spectrum of the underlying supernova, SN 2003dh, became visible. After 34 days its spectrum resembled that of the supernova SN 1998bw of a similar age (dashed line).



Collapsar Model of Gamma-Ray Bursts

This schematic illustrates the **collapsar model** of GRBs. The left image shows a pair of jets being launched from and accretion disk fed by matter falling in.

In the central image the jets have broken through the stellar surface and emit the prompt burst of gamma-rays. Later, the jets slow down and spread out as they plow into surrounding matter, producing the afterglow.



Collapsar Model of Gamma Ray Bursts

The **collapsar model** proposes that a **long gamma ray burst** occurs during a core collapse supernova (Type Ic) of a ~ 30 $M_\odot$ star that is spinning rapidly.

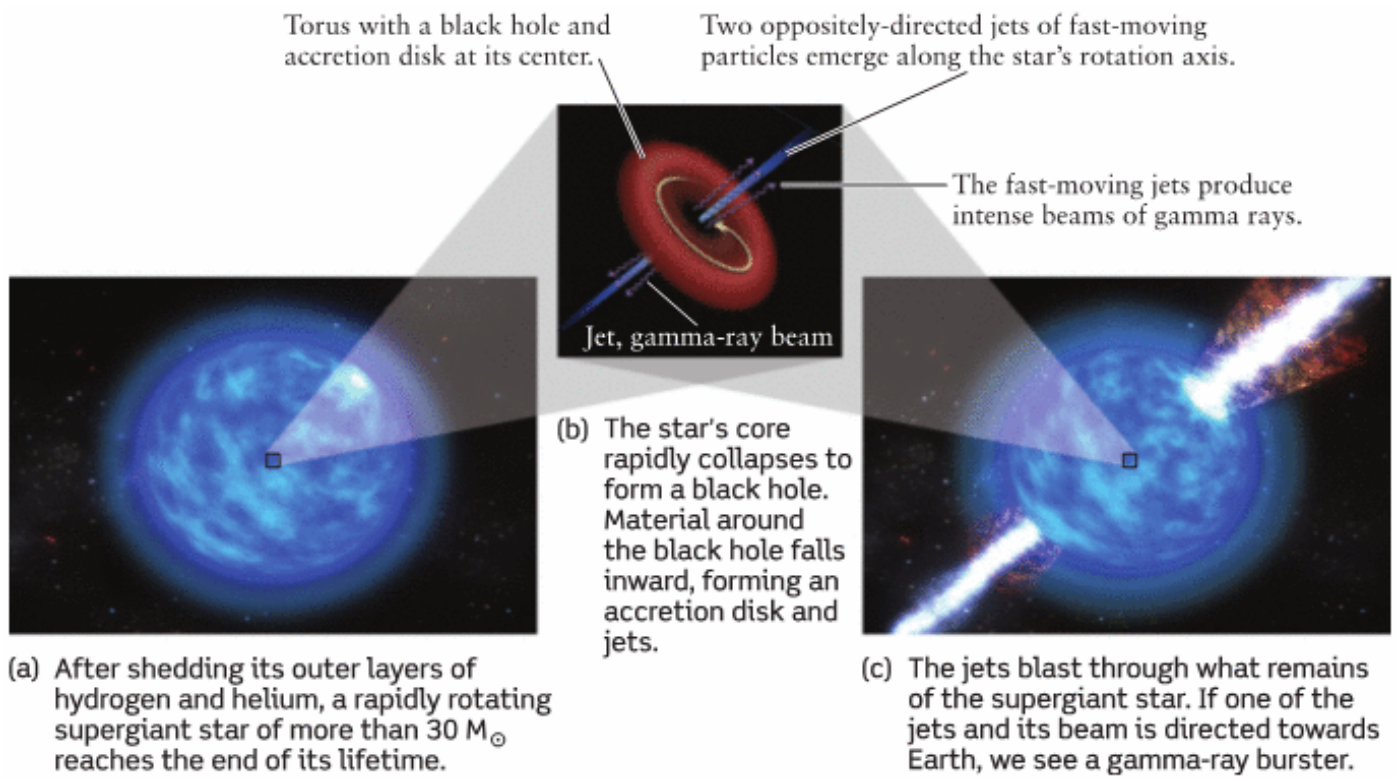
In this model **the core of the star collapses** to form a BH. The material just around the BH forms an accretion disk that is drawn into the BH. The magnetic field of this accretion disk forms jets of charged particles that break through the outer layers of the star.

(Key point: in a Type Ic supernova the outer **H and He layers have been blown away** so its easier for the jets to break through the star)

The energetic particles in the jet produce gamma-rays. If a jet is pointed towards the Earth we see a gamma ray burst.

The accretion disk is sucked into the BH within a few seconds and the gamma-rays burst ends.

Collapsar Model



Beamed radiation: A typical Type Ic supernova releases 10^{46} Joules of energy (0.03% goes into light and the rest mostly into neutrinos)

If we were to assume that all the energy released in a gamma ray burst was distributed uniformly the total energy would be ~ 3×10^{47} Joules but if the energy is beamed then the total energy is less and close to a normal Type Ic.

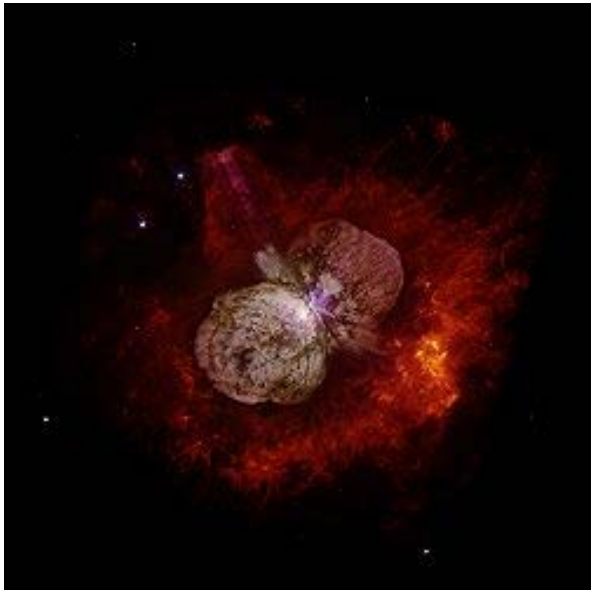
Collapsar Model

Three special conditions are required for a star to evolve all the way to a GRB under the Collapsar Model:

1) the star must be **very massive** (~40 $M_\odot$ on the main sequence) to form a central black hole in the first place,

2) the star must be **rapidly rotating** to develop an accretion disk capable of launching jets, and

3) the star must have **low metallicity** in order to strip off its hydrogen envelope so the jets can reach the surface. As a result, gamma-ray bursts are far rarer than ordinary core-collapse supernovae, which only require that the star be massive enough to fuse all the way to iron.

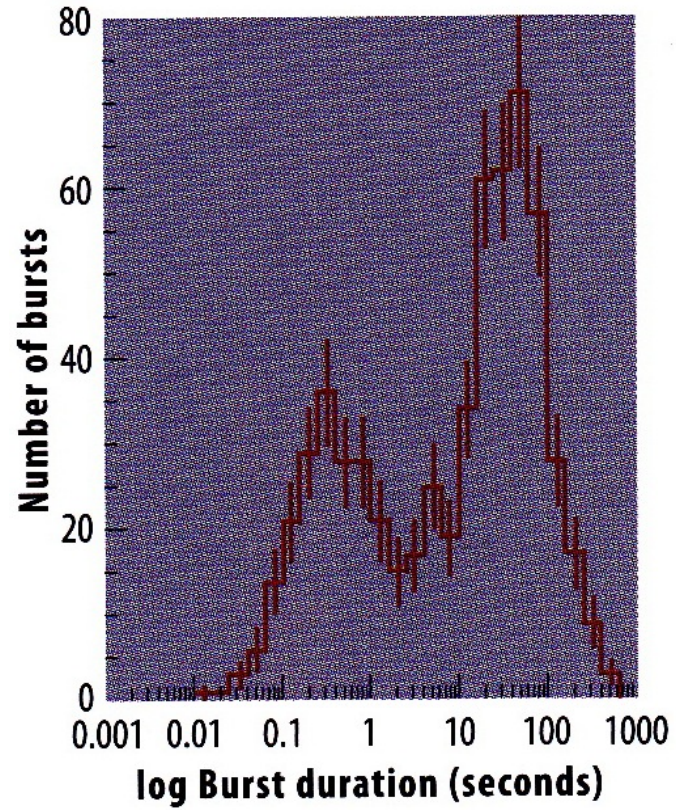


Eta Carinae, in the constellation of Carina, one of the nearer candidates for a hypernova!

Long and Short GRBs

Gamma-ray bursts fall into two types. **Long bursts** ~ 2 - 1000 sec duration and **short bursts** ~ 0.01 sec - 2 sec duration (contain lower energy photons than long bursts)

Their cosmic origin was confirmed with the measurement of their redshift. The spectrum of the **afterglow** is consistent with a Type Ic supernova spectrum.

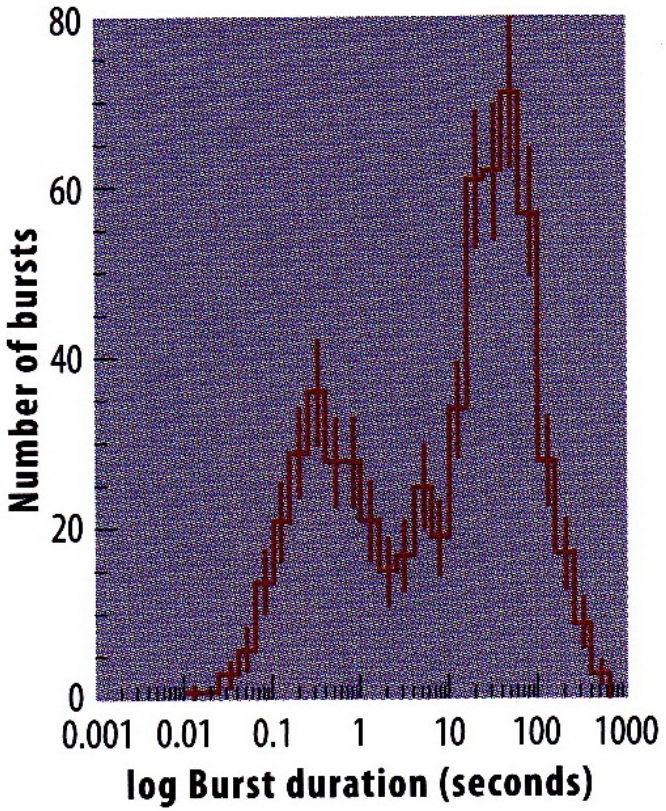


Progenitors of Long GRBs

Long GRBs are found in systems with abundant recent star formation (ie. contain massive stars) , such as in irregular galaxies and **in the arms of spiral galaxies**.

Why are star formation regions likely to contain massive stars?

Follow up observations of several long GRBs have detected emission from type Ib/c supernova at the same location.

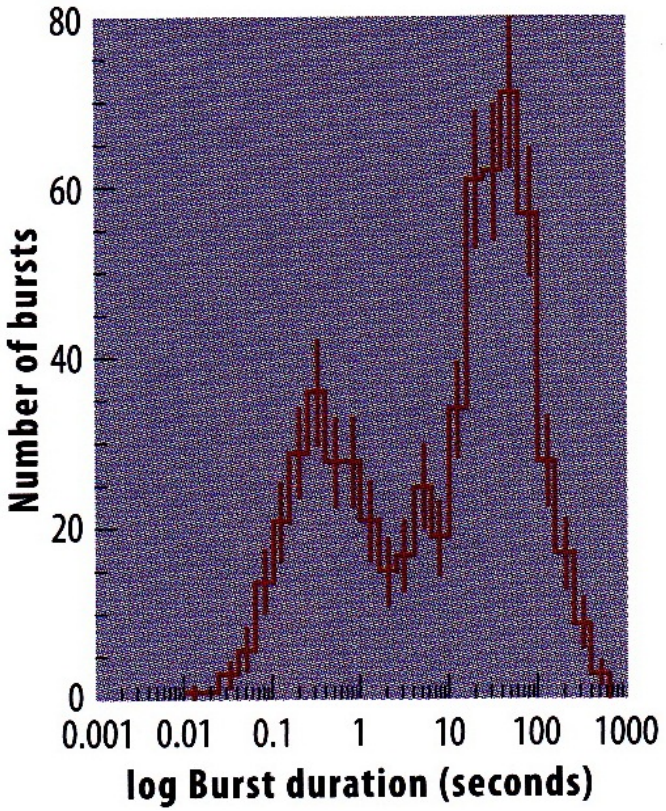


Progenitors of Short GRBs

Several **short GRBs have been associated with** the outer regions and even the outer halo of large **elliptical galaxies** in which star formation has nearly ceased.

All the hosts identified so far have also been at low redshift.

No supernova has been associated with any short GRB.



Models of Short GRBs

One model posits that short GRBs are the result of the merger of two compact objects : two neutron stars, or a black hole and a neutron star.

During the merger immense amount of energy is liberated before the matter plunges into a single black hole.

The whole process is believed to occur extremely quickly and be completely over within a few seconds, accounting for the short nature of these bursts.