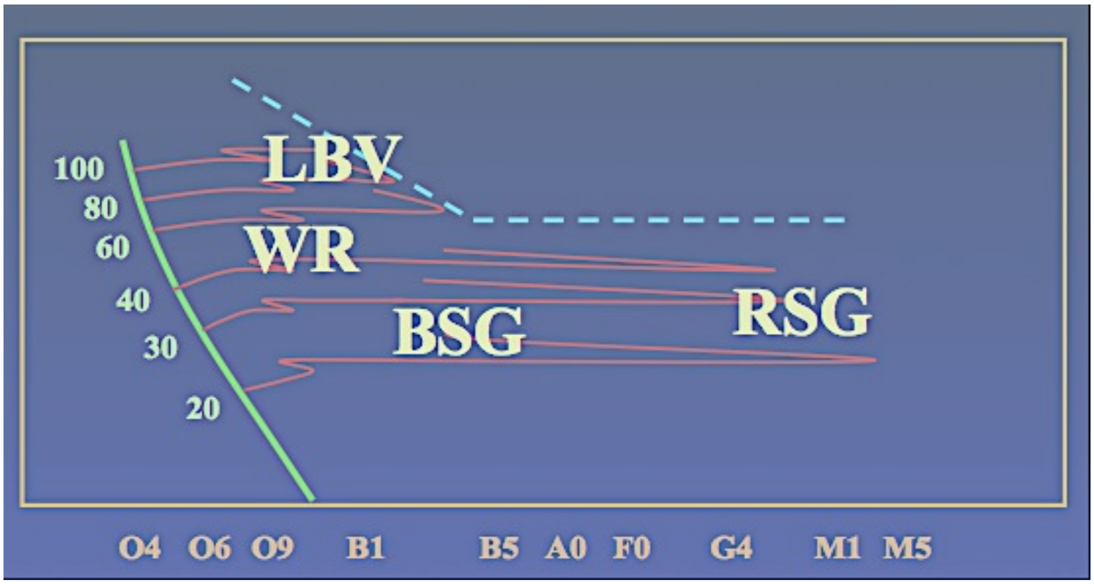
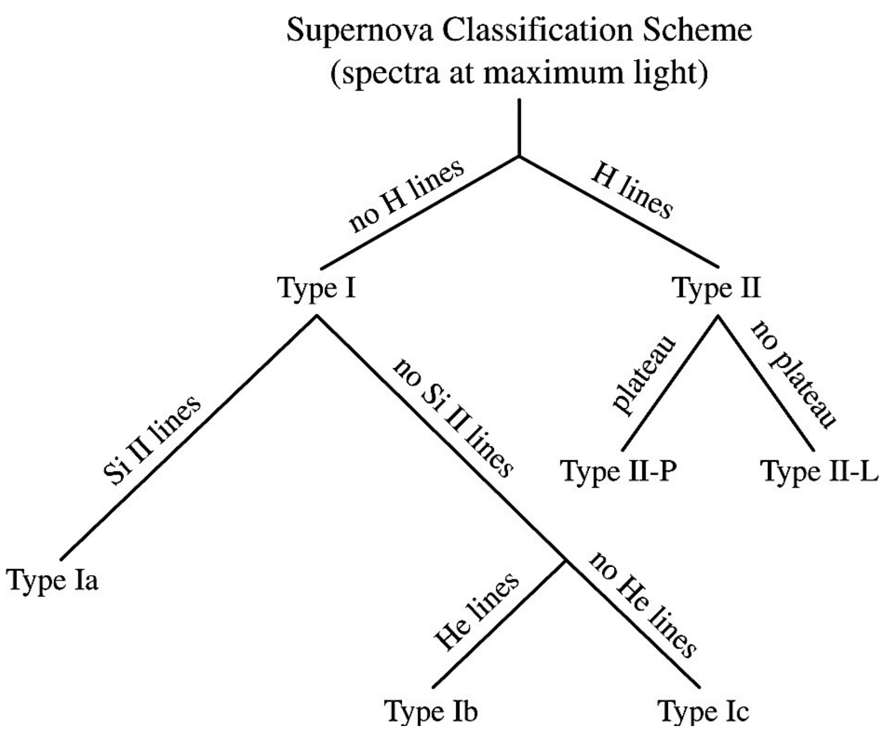
Astronomy 404
November 18, 2013

Chapter 15. The Fate of Massive Stars





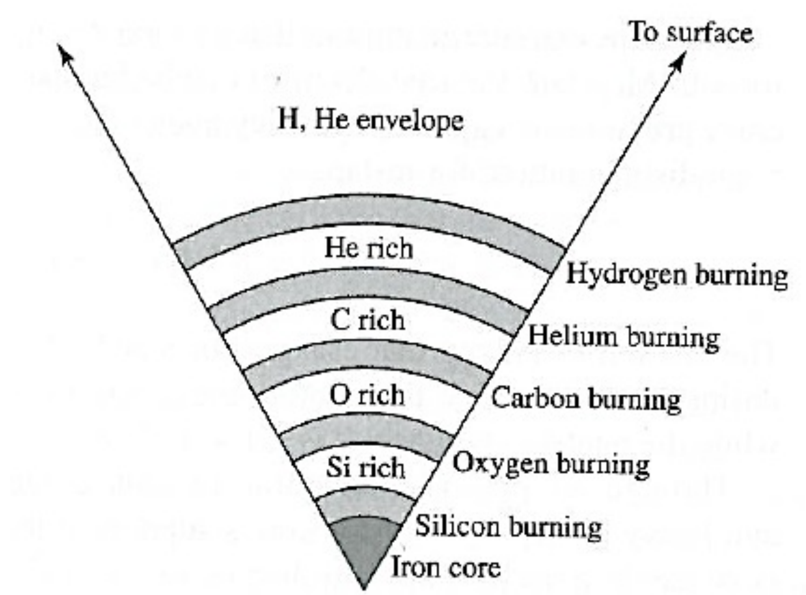
Core-Collapse Supernovae

The collapse of a 3 $M_\odot$ core of a massive star down to 50 km radius releases ~ 10^{46} J of energy. [~ $\frac{3}{10}\frac{G M^2}{R}$]

Only 1% of the energy is in the form of kinetic energy in the supernova ejecta, and 0.1% in the form of radiation. The greatest majority of the energy is radiated away in the form of neutrinos.

H burns in to He. He burns into C and O. C burning generates O, Ne, Na, and Mg. O requires the lowest temperature to burn, so it is the next one to burn (after C).

Toward the end of the stellar evolution, the core of a massive star has an onion-like structure:



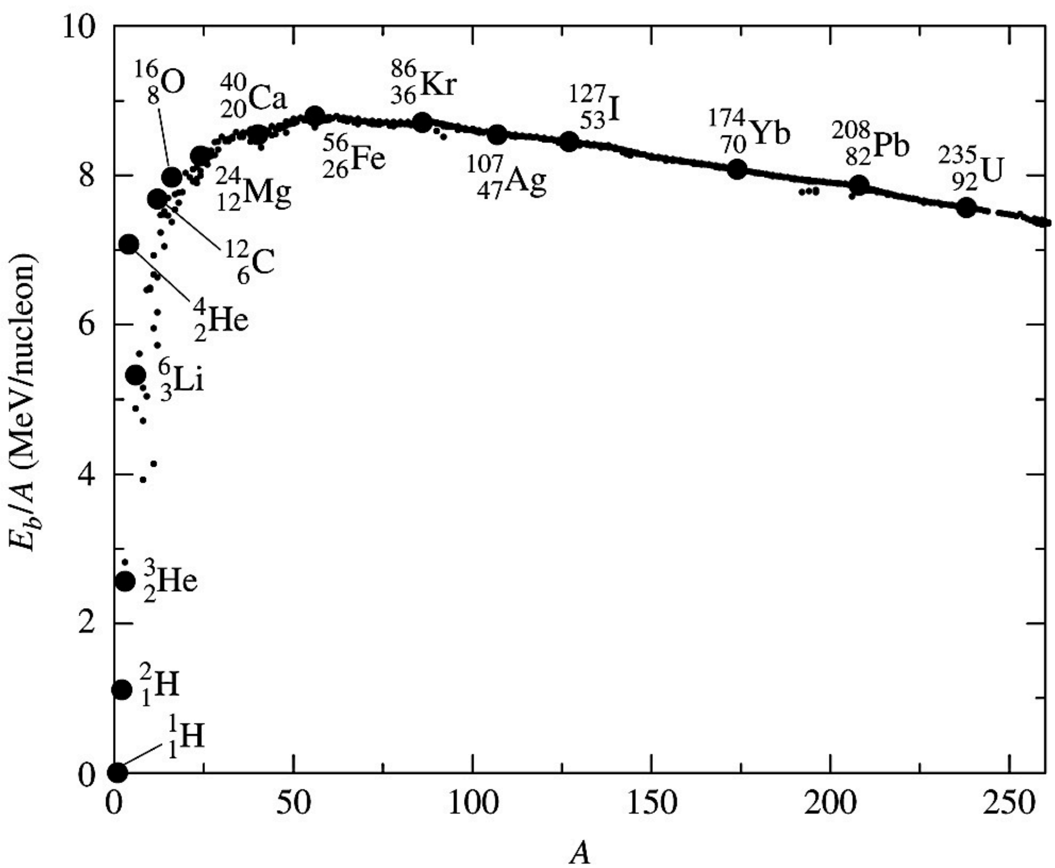
The Si burning in the core at temperature ~ 3×10^9 K goes through a series of reactions and produces iron-peak elements.

$$^{28}_{14}\mathrm{Si} + ^{4}_{2}\mathrm{He} \rightleftharpoons ^{32}_{16}\mathrm{S} + \gamma$$

$$^{32}_{16}\mathrm{S} + ^{4}_{2}\mathrm{He} \rightleftharpoons ^{36}_{18}\mathrm{Ar} + \gamma$$

$$\vdots$$

$$^{52}_{24}\mathrm{Cr} + ^{4}_{2}\mathrm{He} \rightleftharpoons ^{56}_{28}\mathrm{Ni} + \gamma.$$



These Si-burning products in the core are grouped together and called **iron core**.

The burning of elements close to the iron peak releases less energy than H and He, so the duration of each burning lasts shorter and shorter. For a 20 solar mass star:

H-burning	10^7 yr
He-burning	10^6 yr
C-burning	300 yr
O-burning	200 days
Si-burning	2 days

At the high temperature of the core, some photons are energetic enough to destroy heavy nuclei – **photodisintegration**.

$$^{56}_{26}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}_{2}\mathrm{He} + 4n$$

$$^{4}_{2}\mathrm{He} + \gamma \rightarrow 2p^{+} + 2n.$$

The electrons that provided degeneracy pressure are now captured by p^+ to become n. $p^+ + e^- \rightarrow n + \nu_e$.
For a 20 solar mass star, the radiation luminosity is $4.4\text{x}10^{31}$ W, and the neutrino luminosity is $3.1\text{x}10^{38}$ W !

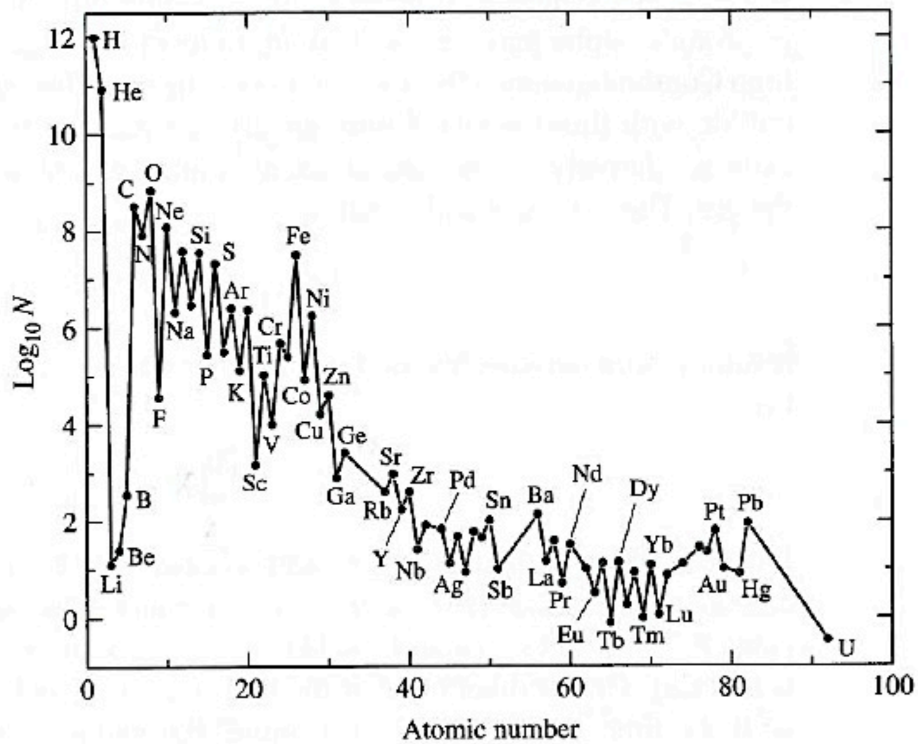
As the core loses pressure, it collapses. Eventually the neutrons' degeneracy pressure stops the collapse to form a neutron star, but if the core mass is too high the collapse leads to the formation of a black hole.

The explosion of a supernova has not been modeled successfully because the treatment of neutrinos is difficult. Adam Burrows modeled an ocean of neutrinos sloshing in the collapsing core and claimed some success.

How does SN ejecta get thrown out at high velocity? Try to drop a ping pong ball on top of a basket ball to the floor and watch the flight of the ping pong ball.

Supernovae eject processed material to enrich the interstellar medium for future star formation. Essentially all heavy elements are produced in stars.

See the solar abundance in the figure below.



Li, Be, and B are under-abundant compared with other elements because they are not prominent end products of nuclear reactions. The solar Li abundance is lower than meteorites' Li abundance, but the Be and B abundances are similar between the Sun and meteorites. It has been suggested that convection brings the surface material down to high-temperature layers where Li and collide with He to burn, but not deep enough for Be to burn. However, stellar model shows that the convection does not go down to Li-burning temperature – the **solar lithium problem.**

s-Process and r-Process Nucleosynthesis

It is easier to build heavier nuclei by absorbing a neutron:

$$^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma$$

If the new nucleus is unstable, it can go through a beta-decay:

$$^{A+1}_{Z}X \rightarrow {}^{A+1}_{Z+1}X + e^{-} + \overline{\nu}_e + \gamma$$

If the neutron capture time scale is longer than the beta-decay time scale, it is a slow process, an ***s-process*** reaction.
If the neutron capture time scale is shorter than the beta-decay time scale, it is a fast process, an ***r-process*** reaction.

The s-process reactions occur in normal stellar evolution, while the r-process reactions can happen in supernovae.

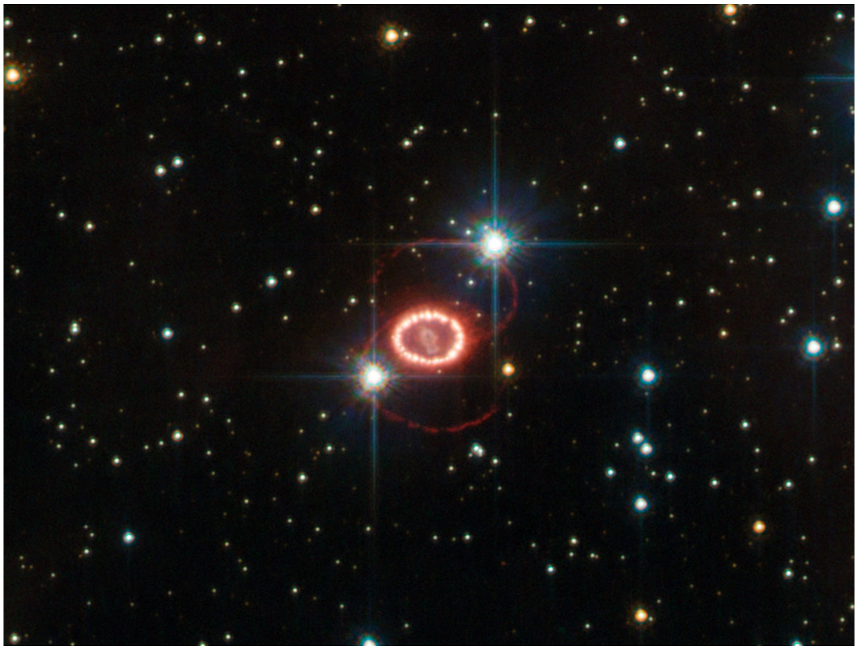
The r-process reactions can explain the abundance ratios of nuclei with atomic number A > 60.

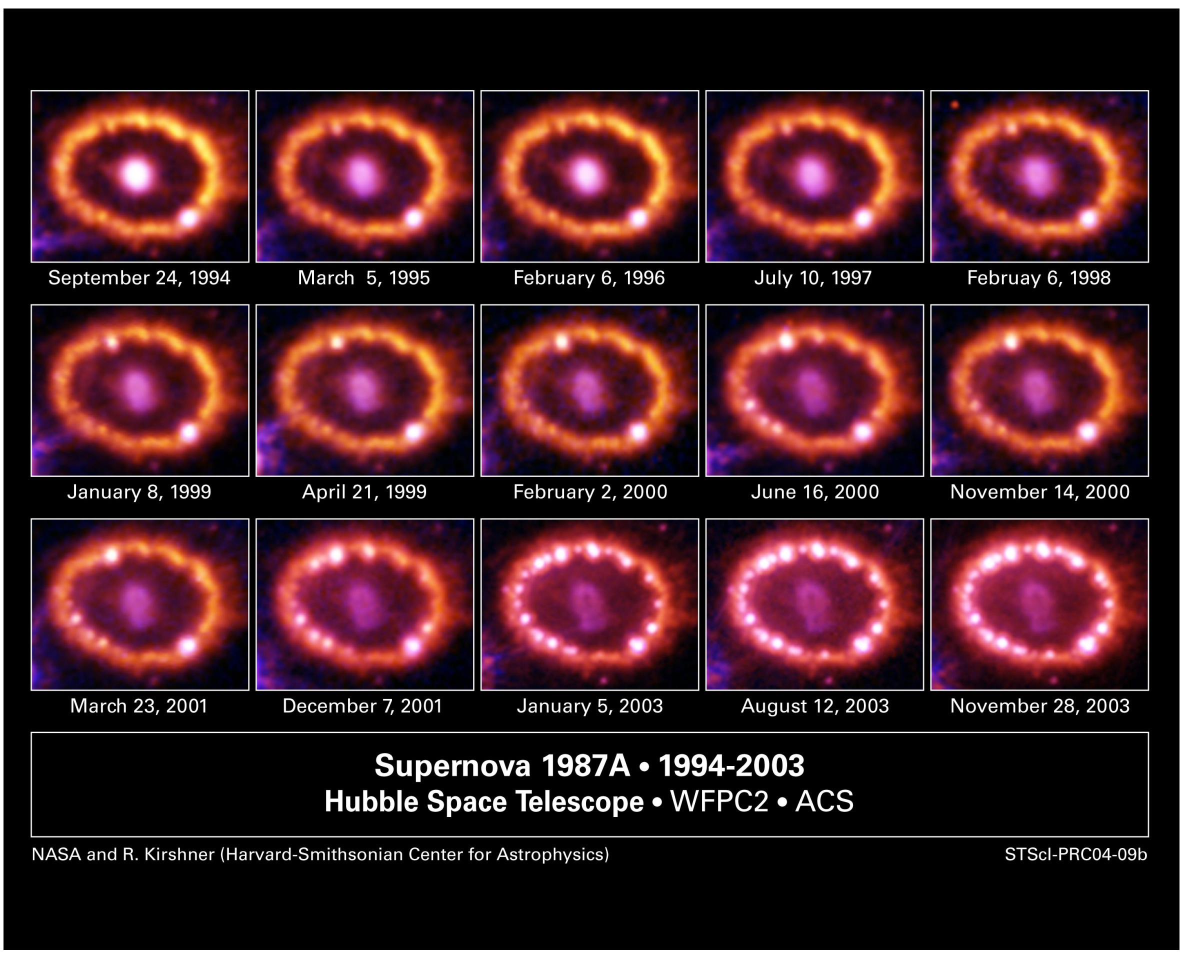
SN 1987A

SN 1987A's progenitor was a B3I. It was under-luminous.
No compact remnant (neutron star) is detected.
Neutrinos from SN1987A was detected for 12.5 seconds, 3 hours before the SN light reached the Earth.

We are witnessing SN ejecta shocking the circumstellar ring.

The progenitor may be a binary (to be checked in the future).

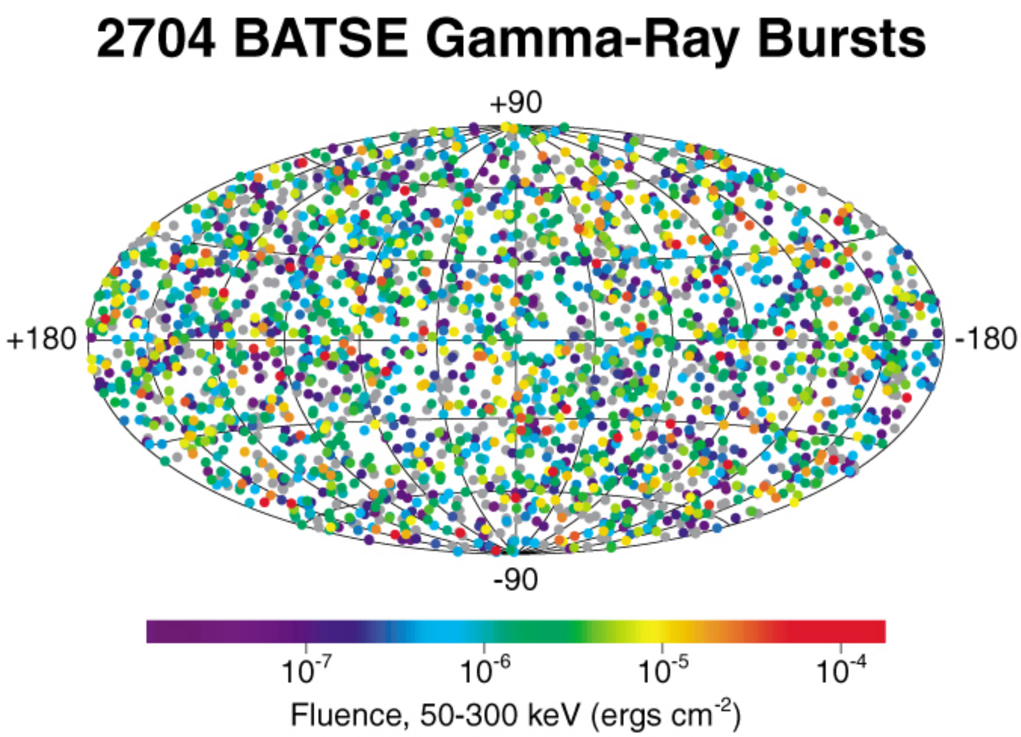



September 24, 1994
March 5, 1995
February 6, 1996
July 10, 1997
Februay 6, 1998
January 8, 1999
April 21, 1999
February 2, 2000
June 16, 2000
November 14, 2000
March 23, 2001
December 7, 2001
January 5, 2003
August 12, 2003
November 28, 2003
Supernova 1987A • 1994-2003
Hubble Space Telescope • WFPC2 • ACS
NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
STScI-PRC04-09b

Gamma-Ray Bursts

In the 1960's, the Vela series of military satellites monitored the gamma-ray emission from the ground to see if the Russians conducted nuclear tests. They detected no such events, but gamma-ray bursts (GRBs) from the sky. The information was not released until 1973.

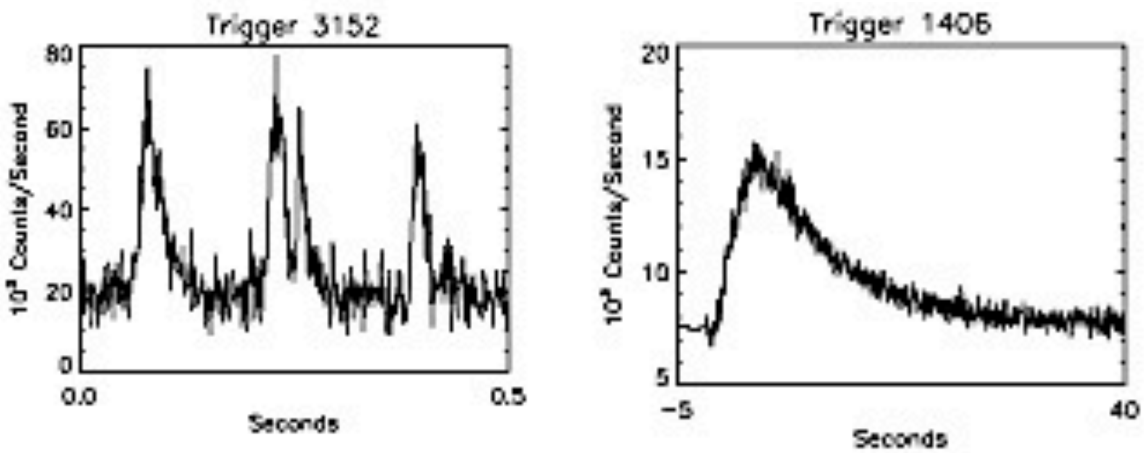
The distribution of GRBs is isotropic. Below is a map from the Compton Gamma-Ray Observatory (CGRO) Burst and Transient Source Experiment (BATSE) observations.



The energies of the gamma-ray photons range from 10's of keV to many GeV.

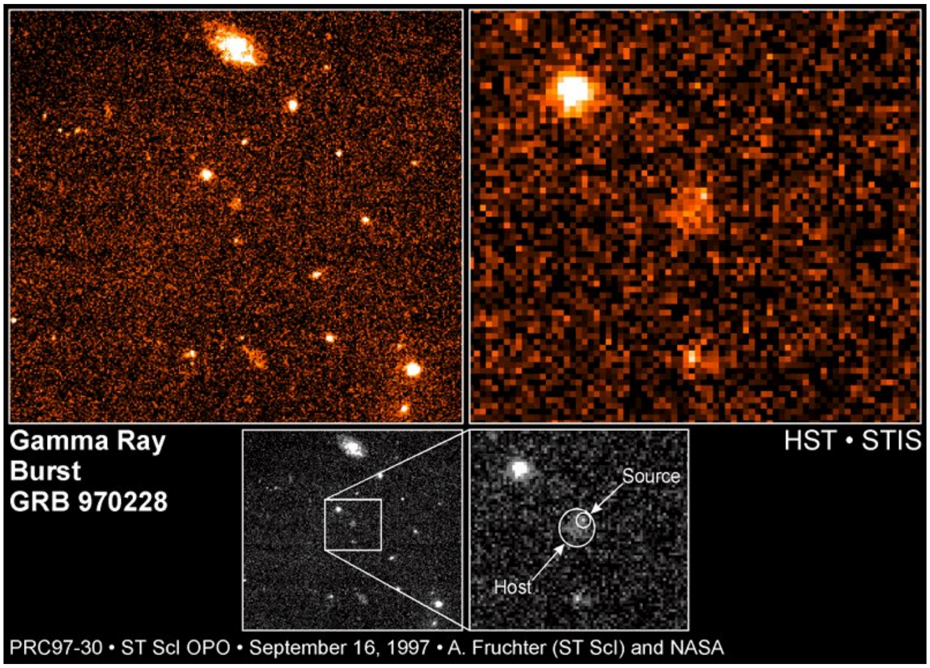
The bursts last from 10^{-2} to 10^{3} seconds, but the rise time is as short as 10^{-4} sec, which implies that the responsible object is as small as $\sim 10^{-4}\, c$ = 30 km, and neutron stars must be involved.

GRBs are divided into two categories: **short-hard** (< 2 sec) and **long-soft** (> 2 sec).



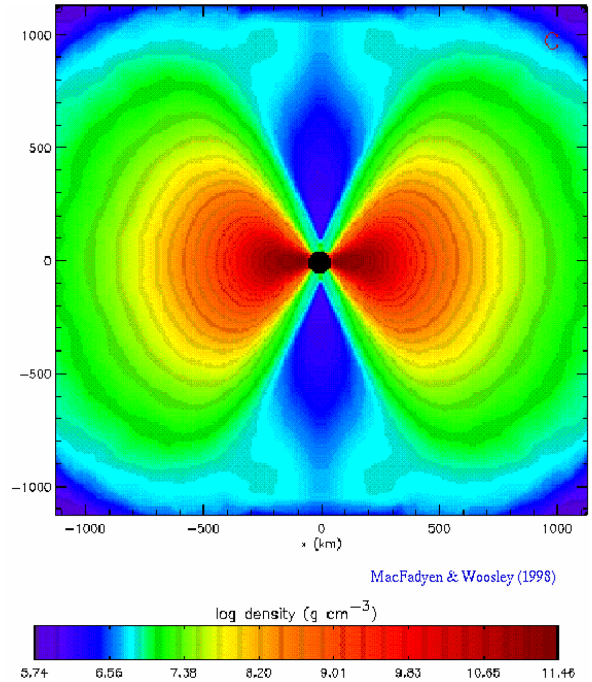
There have been thousands of papers speculating whether GRBs are in the Milky Way or extragalactic.

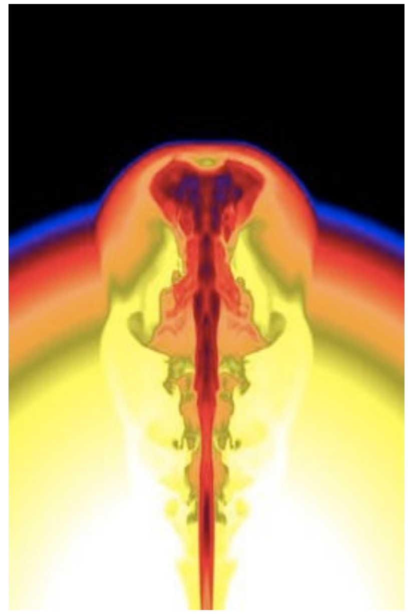
In 1997, the BeppoSAX satellite detected GRB 970228 and localized its X-ray position to within 3’, allowing HST and Keck to carry out follow-up observations. Its host galaxy was identified and its redshift was later measured. Cosmological distance!



In 1998, GRB 980425 was identified with the SN 1998bw, a particular energetic Type Ib or Ic supernova, 2-6×10^{45} J, ~30 times as energetic as regular SN Ib/Ic. More connections between the long-soft GRBs and SNe were subsequently established.

Collapsar (hypernova) model of a GRB by MacFadyen & Woosley. The massive star has a rapid rotation. As the core collapses into a neutron star or a black hole, an accretion disk and bipolar relativistic jets are formed. The jet breaks out and is observed as a a long-soft GRB. The gamma-ray emission is NOT isotropic.





The short-hard GRBs have a different origin, most likely involving mergers of two neutron stars or a neutron star and a black hole.