Lecture 17:

Supernovae and Neutron Stars

http://apod.nasa.gov/apod/

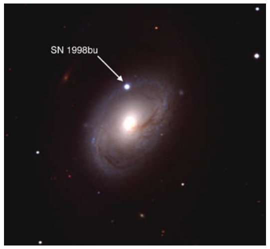
SUPERNOVAE

- A supernova is the explosive death of a star. Unlike an ordinary nova, it does not repeat.
- Two types are easily distinguishable by their spectrum. Type II has hydrogen (H_α). Type I does not.
- Very luminous. Typical luminosities range from a few times 10^{42} erg s^{-1} (relatively faint Type II; about 300 million L_{sun}) to 2 x 10^{43} erg s^{-1} (Type Ia; 6 billion L_{sun}) - roughly as bright as a small galaxy.

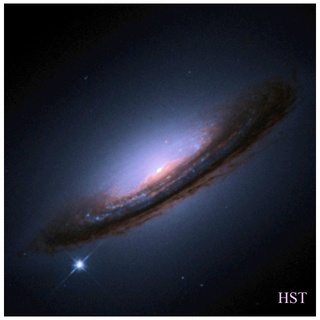
  (Recently some rare supernovae have been discovered to be even brighter)

SN 1998aq

SN 1998dh



SN 1998bu



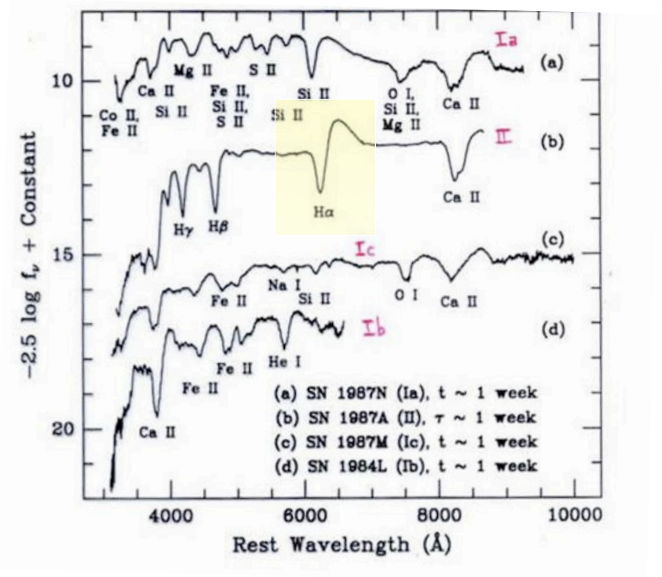
SN 1994D

For several weeks a supernova's luminosity rivals that of a large galaxy.

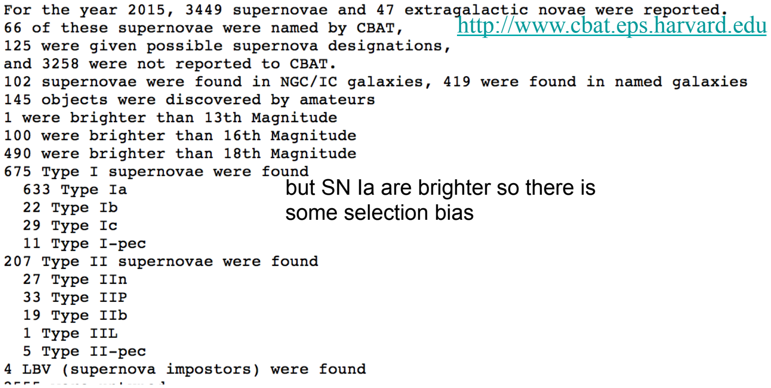
Supernovae are named for the year in which they occur + A .. Z, aa – az, ba – bz, ca – cz, etc
Currently at SN 2016aqz (3/1/16)

http://www.rochesterastronomy.org/supernova.html - 2016X

SPECTROSCOPICALLY



How many supernovae?



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For the year 2015, 3449 supernovae and 47 extragalactic novae were reported.
66 of these supernovae were named by CBAT,
125 were given possible supernova designations,
and 3258 were not reported to CBAT.
102 supernovae were found in NGC/IC galaxies, 419 were found in named galaxies
145 objects were discovered by amateurs
1 were brighter than 13th Magnitude
100 were brighter than 16th Magnitude
490 were brighter than 18th Magnitude
675 Type I supernovae were found
  633 Type Ia
  22 Type Ib
  29 Type Ic
  11 Type I-pec
207 Type II supernovae were found
  27 Type IIn
  33 Type IIP
  19 Type IIb
  1 Type IIL
  5 Type II-pec
4 LBV (supernova impostors) were found
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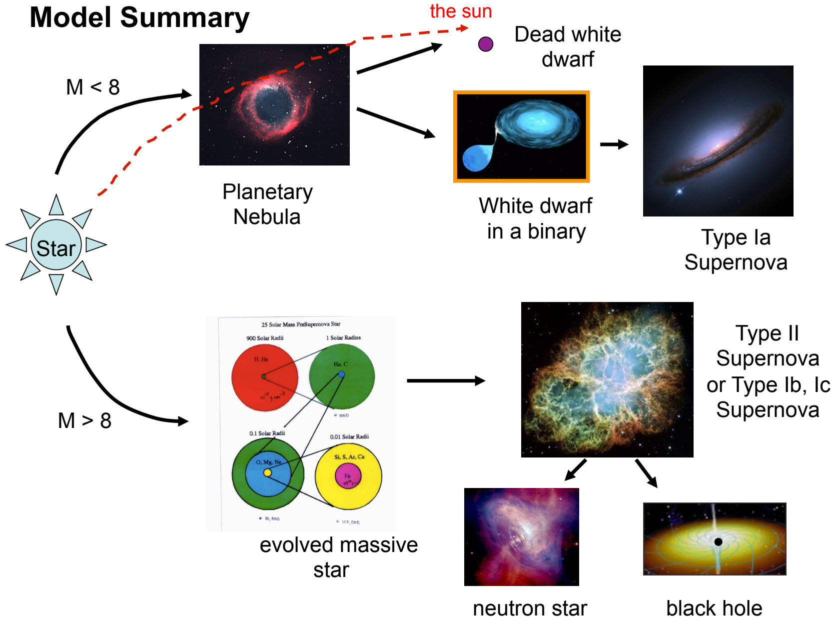
http://www.cbat.eps.harvard.edu

but SN Ia are brighter so there is some selection bias

Theoretically there are several supernovae per second in the observable universe. Their neutrinos add up to a cosmic background of ~10 neutrinos/cm^2/sec. This may be detected soon

http://lanl.arxiv.org/abs/1004.3311v1

Model Summary



the sun

M < 8

Star

M > 8

Planetary Nebula

Dead white dwarf

White dwarf in a binary

Type Ia Supernova

evolved massive star

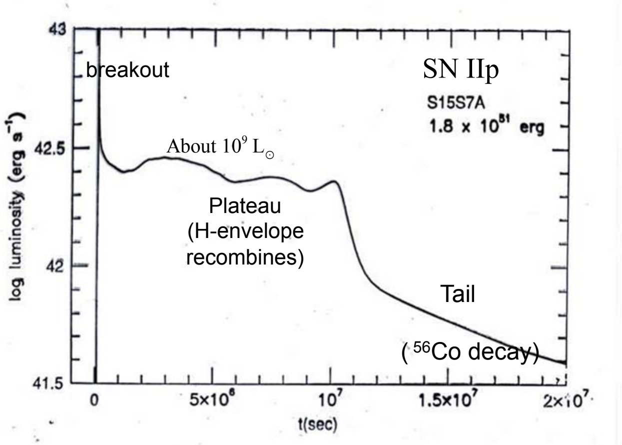
Type II Supernova or Type Ib, Ic Supernova

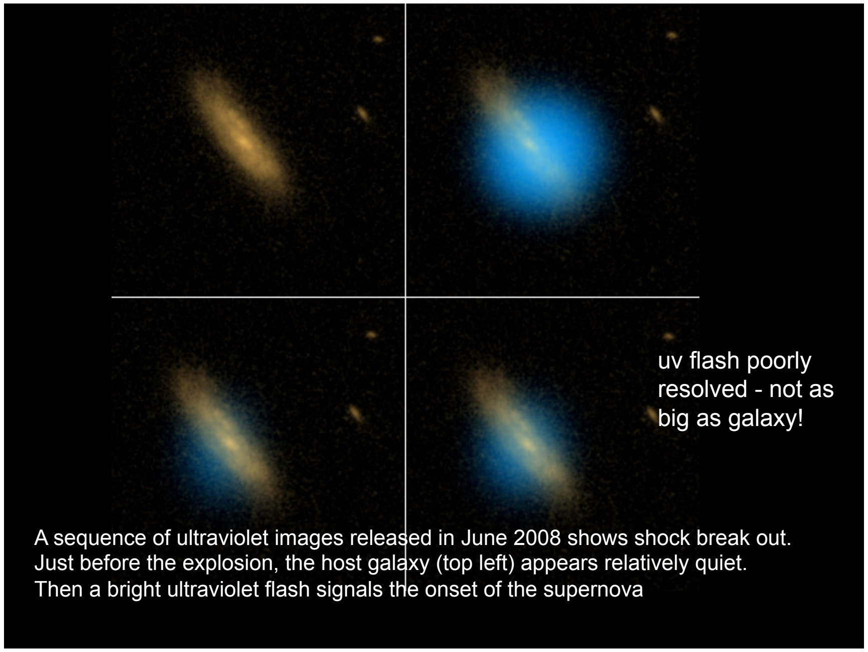
neutron star

black hole

Light Curve of Type IIp Supernovae

- The most common kind of supernova (in a volume-limited sample). Death of a massive star that still has its hydrogen envelope. The star is a red (usually) or blue (rarely) supergiant when it dies.
- There are three stages – shock breakout, the “plateau”, and the decline.
- Breakout is the first time the supernova brightens. The shock wave erupts from the surface heating it to about 200,000 K for about 2000 s. It declines to 30,000 K after one day. Meanwhile the luminosity declines from about 10^{11} solar luminosities to about 10^9 solar luminosities. This emission, in UV has been seen in at least two supernovae less than one day after their explosion (Gezzari et al 2008)





A sequence of ultraviolet images released in June 2008 shows shock break out. Just before the explosion, the host galaxy (top left) appears relatively quiet. Then a bright ultraviolet flash signals the onset of the supernova

Light Curve of Type IIp Supernovae (cont'd)

- As the hydrogen envelope expands and cools it eventually reaches 5500 K where the hydrogen starts to recombine. This recombination moves into the expanding envelope as a wave over a period of about 3 months. The recombination reduces the opacity and lets out the energy deposited by the shock as it passed through the envelope. This is the plateau. The temperature stays pegged to 5500 K.

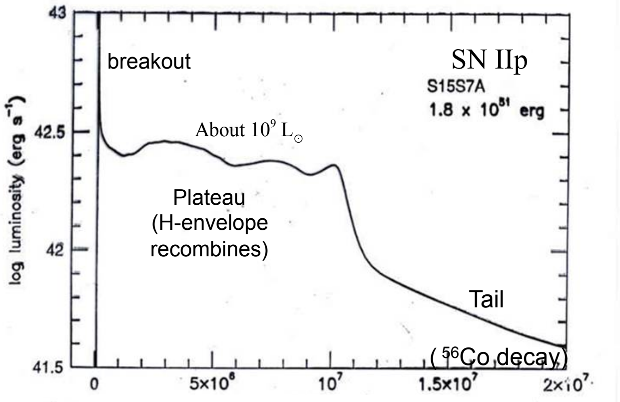
- Still later the decay of radioactivity produced in the supernova keeps it bright for years.

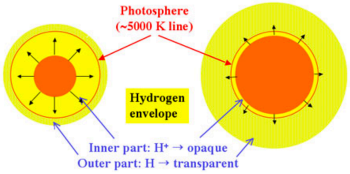
$$^{56}\text{Ni} + e^- \rightarrow {}^{56}\text{Co} + \nu_e + \gamma \quad (6.1 \text{ days})$$

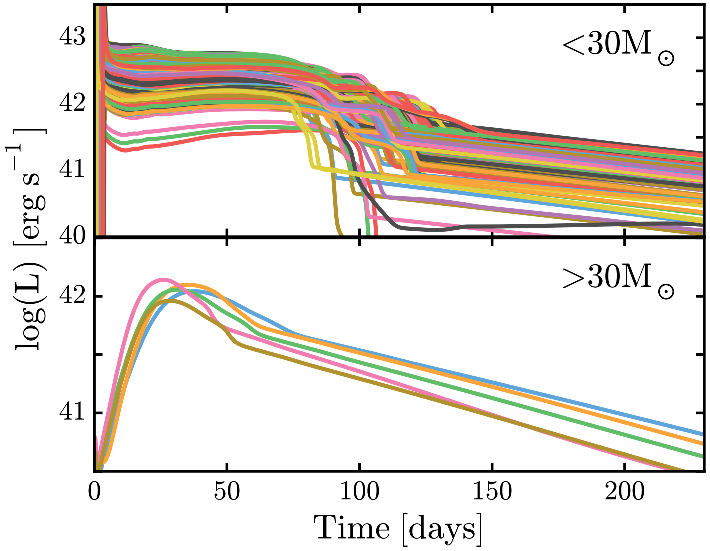
$$^{56}\text{Co} + e^- \rightarrow {}^{56}\text{Fe} + \nu_e + \gamma \quad (77 \text{ days})$$

Together these release 9.4 x 10^{16} erg g^{-1}. Thus 0.1 solar masses of ^{56}Ni releases 2 x 10^{49} erg

Theoretical light curve of a Type IIp supernova

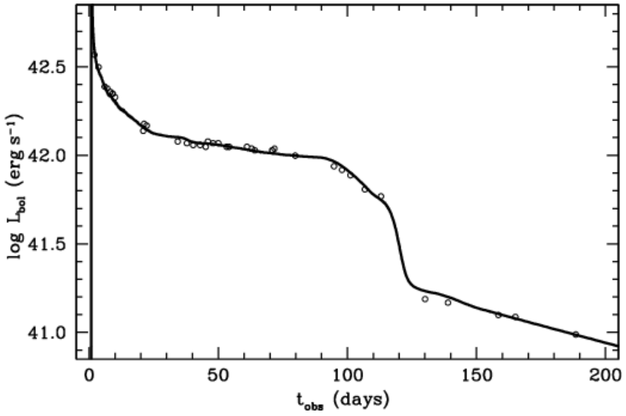






Sukhbold, Woosley, et al (2016)

Model and data for SN 1999em



Elmhamdi et al (2003)

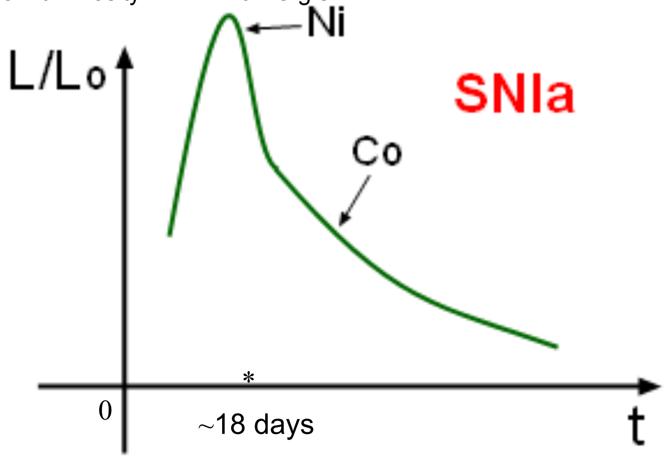
Type IIp Supernovae (cont’d)

- The spectrum is dominated by the Balmer lines of hydrogen. On the plateau the spectrum is dominatly absorption lines, but at late time as the supernova becomes a nebula, one sees emission lines
- Radii inferred on the plateau are about 10^{15}cm (100 AU). The emission resembles a blackbody with T_{eff} approximatey 5500 K
- Type II supernovae always leave behind either a neutron star or a black hole. In many instances the neutron star is a “pulsar”

Type I Supernovae

- Type I supernovae lack hydrogen and thus have no plateau stage. The shock break out is also considerably fainter and shorter in wavelength (x-rays)
- The Type I supernova light curve is thus powered at all times by the decay of radioactive ^{56}Ni and ^{56}Co.
- Type I supernovae are segregated into several classes: Type Ia, Ib, and Ic depending upon special features in their spectra (Si II, He I) and where they are found.
- Type Ib and Ic are also the death of a massive star but one that has lost its envelope – most of the time to a binary companion. Type IIp and Ib/c are found in star forming regions

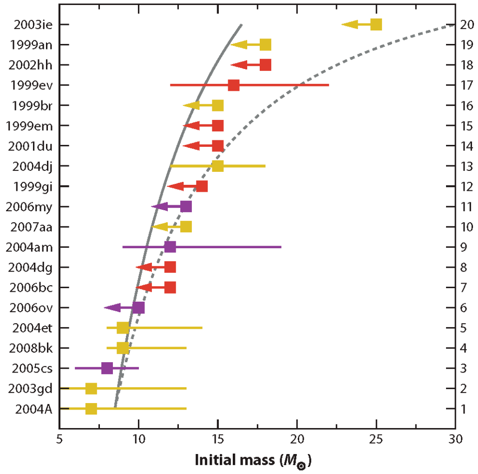
peak absolute magnitude is about -19
peak luminosity 1 – 2 x 10^{43} erg s^{-1}



Type I Supernovae (cont'd)

- Type Ia supernovae are **not** found in star forming regions. They show no preference for spiral arms and can occur in elliptical galaxies where the star formation rate is very low
- While the progenitor stars of about 10 Type II supernovae have been seen before they exploded (e.g. 1987A), no progenitor of a SN Ia has ever been identified. They must be faint
- Type Ia supernovae are brighter than any other class. Type I supernovae in general are bright a shorter time than SN IIp (weeks rather than months)
- Neutron stars and black holes may be produced by Type Ib and Ic supernovae, but never by Type Ia.

Presupernova stars – Type Iip



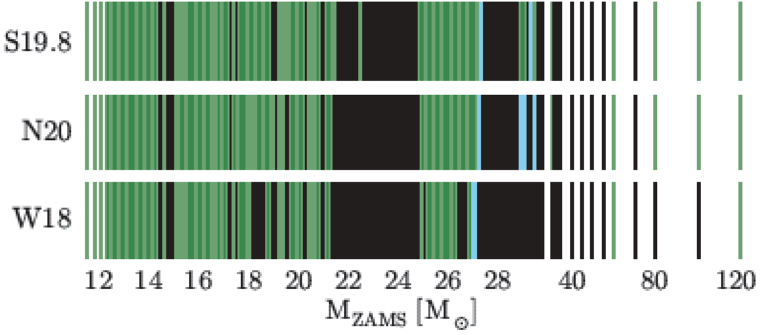
Smartt, 2009 *ARAA*

Progenitors heavier than 20 solar masses excluded at the 95% confidence level.

The solid line is for a maximum mass of 16.5 solar masses.
The dashed line is for a maximum of 35 solar masses

In practice, theorists have struggled for 45 years to get the model just described to work. Sometimes the neutrinos turn around the imploding matter and the star blows up. Sometimes they don't and a black hole is born.

The average supernova mass is about 12 - 13 $M_{\odot}$



It turns out to be harder to blow up high mass stars than low mass ones (gravitational binding goes as M^2)
10 $M_{\odot}$ stars blow up robustly. 30 $M_{\odot}$ stars do not

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Supernovae - General

- In a Type II or Ibc supernova most of the energy comes out in the neutrino burst – 3 x 10^{53} erg. 300 times less is in the kinetic energy of the explosion – 10^{51} erg – and 100 times less than that, 10^{49} erg, is in the light. Bright as they are the electromagntic radiation emitted by a supernova is a small part of its energy budget.
- The kinetic energy and total light output of SN II and SN I of all subtypes are comparable (though SN Ia are brighter), but a SN Ia emits no neutrino burst.
- The velocities of supernovae typically range from 2000 to 20,000 km $s^{-1.}$ The highest velocities are seen early on. Type I supernovae expand faster than Type II.

Supernova 1987A A Type II supernova

before

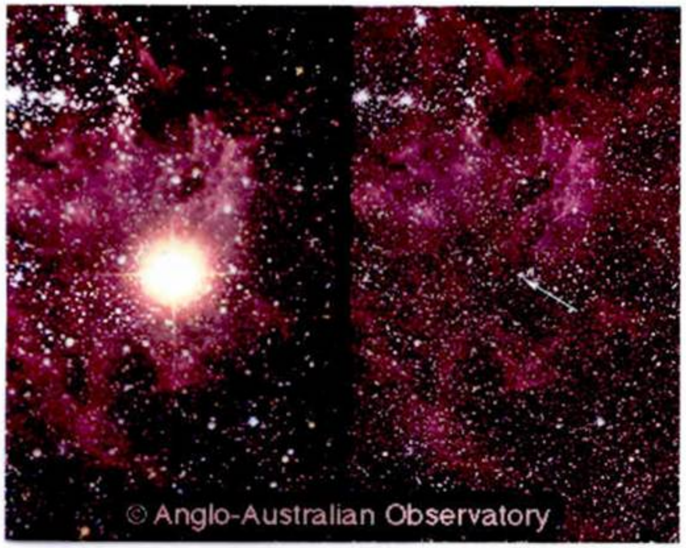
after

February 23, 1987
(+160,000 years)

Brightest supernova in over 400 years.

In the 30 Doradus H II region in the Large Magellanic Cloud.

Progenitor star was a previously catalogued blue supergiant Sk 202-69. Mass = 18 solar masses.



SN 1987A Today

A time sequence of Hubble Space Telescope images, showing the collision of the expanding supernova remnant with a ring of dense material ejected by the progenitor star 20,000 years before the supernova.

Supernovae - General

- There have been 6 supernovae visible to the unaided eye in the last 1000 years. The last one before SN 1987A was Kepler's supernova in 1604. This was about 2.5 kpc away and reached a magnitude of -2.5. The brightest supernova in history was SN 1006 which reached magnitude -8 to -10, as bright a a quarter moon.
- About two Type II supernovae are thought to occur in our galaxy every century and about one Type Ia every other century. Most have gone undetected.
- We see many more supernovae – hundreds each year – in other galaxies
- Supernovae have produced most of the elements heavier than nitrogen

Supernova

(Death of a star)

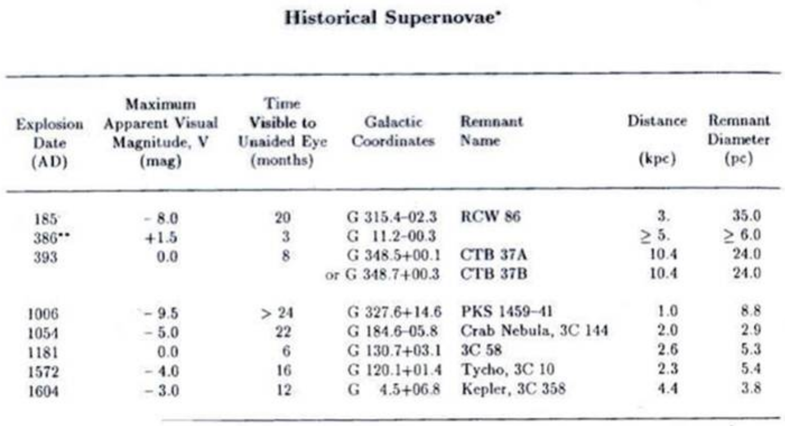
Type Ia (TBD)

- No hydrogen
- Thermonuclear explosion of a white dwarf star
- No bound remnant
- ~10^{51} erg kinetic energy
- v ~ 5,000 – 30,000 km s^{-1}
- No neutrino burst
- $E_{optical}$ ~ 10^{49} erg
- L_{peak} ~ 10^{43} erg s^{-1} for 2 weeks
- Radioactive peak and tail (^{56}Ni, ^{56}Co)
- 1/200 yr in our Galaxy
- Makes about 2/3 of the iron in the Galaxy

Type II

- Hydrogen in spectrum
- M > 8 solar masses
- Iron core collapses to a neutron star or black hole
- ~10^{51} erg kinetic energy
- v ~ 2,000 – 30,000 km s^{-1}
- Neutrino burst ~ 3 x 10^{53} erg
- $E_{optical}$ ~ 10^{49} erg
- L_{peak} ~ 3 x 10^{42} erg s^{-1} for about 3 months (varies from event to event)
- Radioactive tail (^{56}Co)
- 2/100 yr in our Galaxy
- Makes about 1/3 iron and all the oxygen plus many other elements

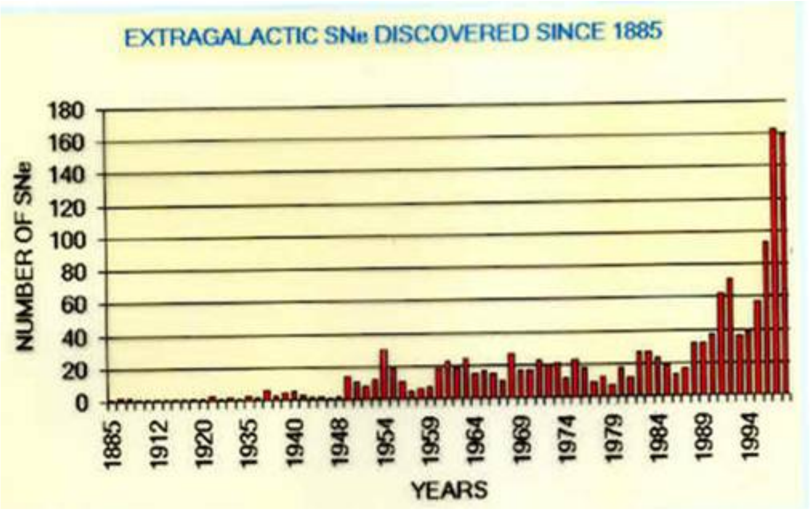
There are also Type Ib and Ic supernovae that share many of the properties of Type II but have no hydrogen in their spectra



Historical Supernovae*

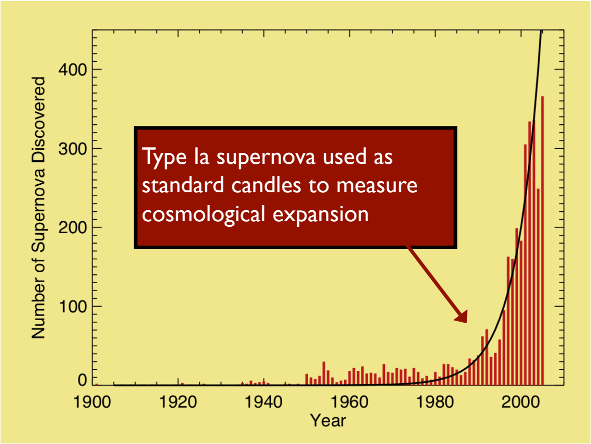
Explosion Date (AD)	Maximum Apparent Visual Magnitude, V (mag)	Time Visible to Unaided Eye (months)	Galactic Coordinates	Remnant Name	Distance (kpc)	Remnant Diameter (pc)
185	- 8.0	20	G 315.4-02.3	RCW 86	3.	35.0
386**	+1.5	3	G 11.2-00.3		≥ 5.	≥ 6.0
393	0.0	8	G 348.5+00.1	CTB 37A	10.4	24.0
			or G 348.7+00.3	CTB 37B	10.4	24.0
1006	- 9.5	> 24	G 327.6+14.6	PKS 1459-41	1.0	8.8
1054	- 5.0	22	G 184.6-05.8	Crab Nebula, 3C 144	2.0	2.9
1181	0.0	6	G 130.7+03.1	3C 58	2.6	5.3
1572	- 4.0	16	G 120.1+01.4	Tycho, 3C 10	2.3	5.4
1604	- 3.0	12	G 4.5+06.8	Kepler, 3C 358	4.4	3.8

1680 Casseopeia-A



Supernova Discovery History

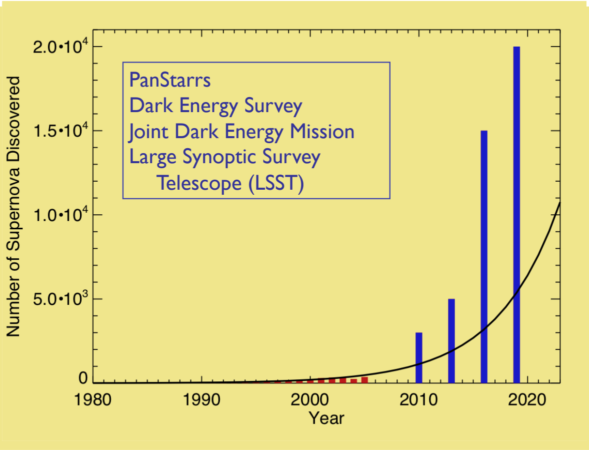
Asiago Catalog (all supernova types)



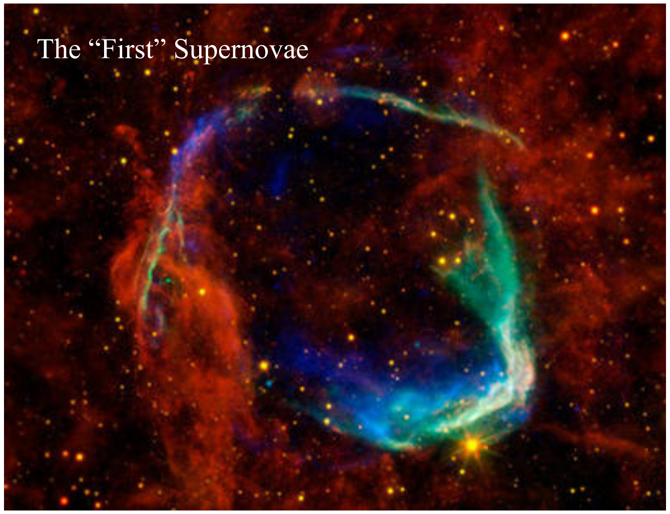
Type Ia supernova used as standard candles to measure cosmological expansion

Supernova Discovery Future

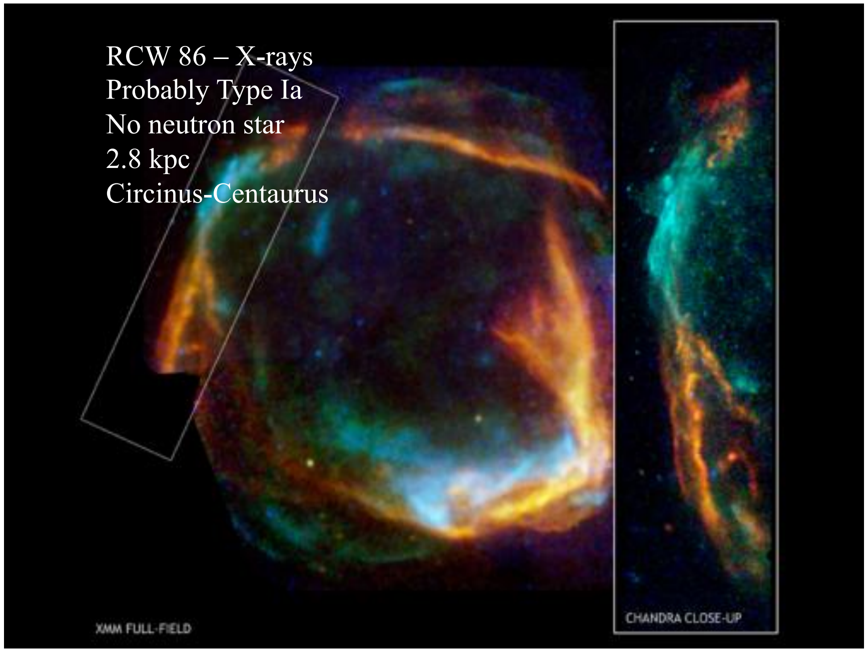
Rough predictions and promises…



The "First" Supernovae

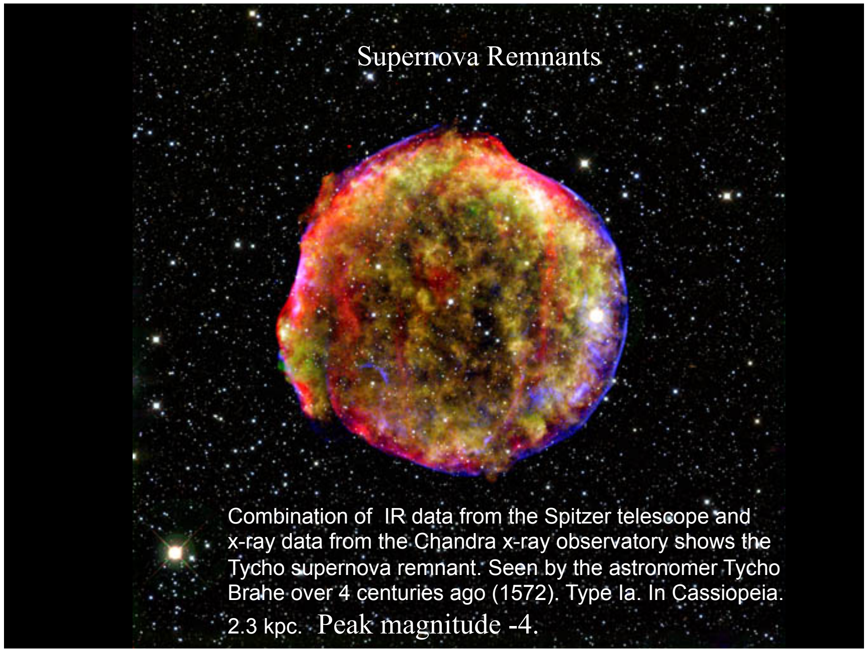


Oldest recorded supernova, RCW 86, first documented by the Chinese in December, 185 A.D. (WISE telescope – infrared)

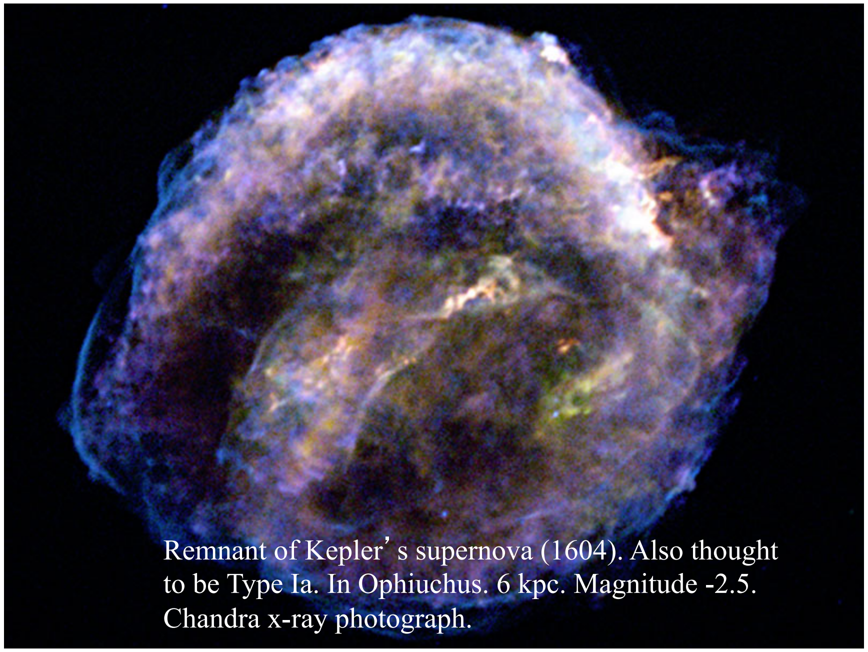


RCW 86 – X-rays
Probably Type Ia
No neutron star
2.8 kpc
Circinus-Centaurus

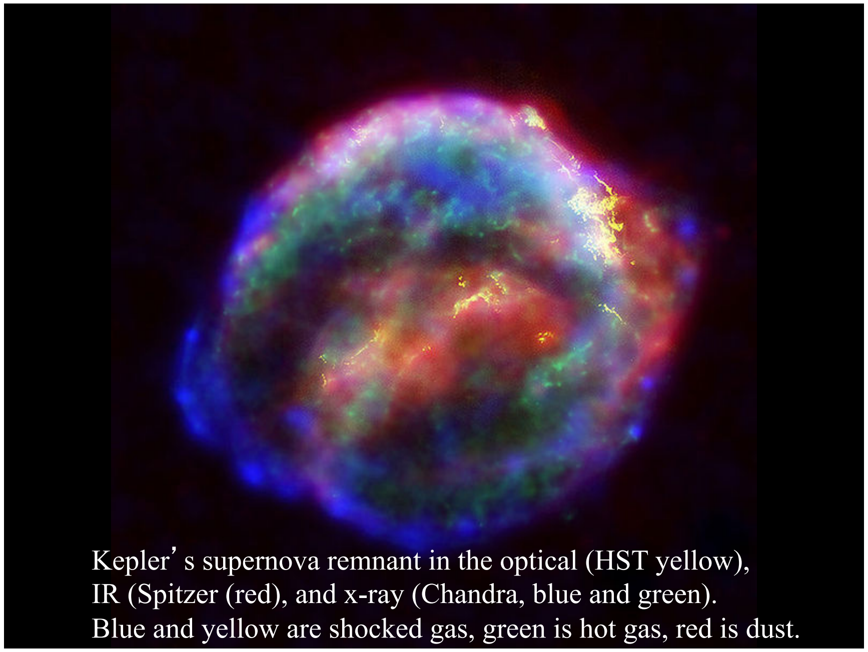
Supernova Remnants



Combination of IR data from the Spitzer telescope and x-ray data from the Chandra x-ray observatory shows the Tycho supernova remnant. Seen by the astronomer Tycho Brahe over 4 centuries ago (1572). Type Ia. In Cassiopeia. 2.3 kpc. Peak magnitude -4.

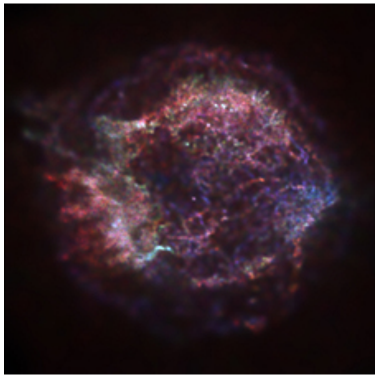


Remnant of Kepler’ s supernova (1604). Also thought
to be Type Ia. In Ophiuchus. 6 kpc. Magnitude -2.5.
Chandra x-ray photograph.



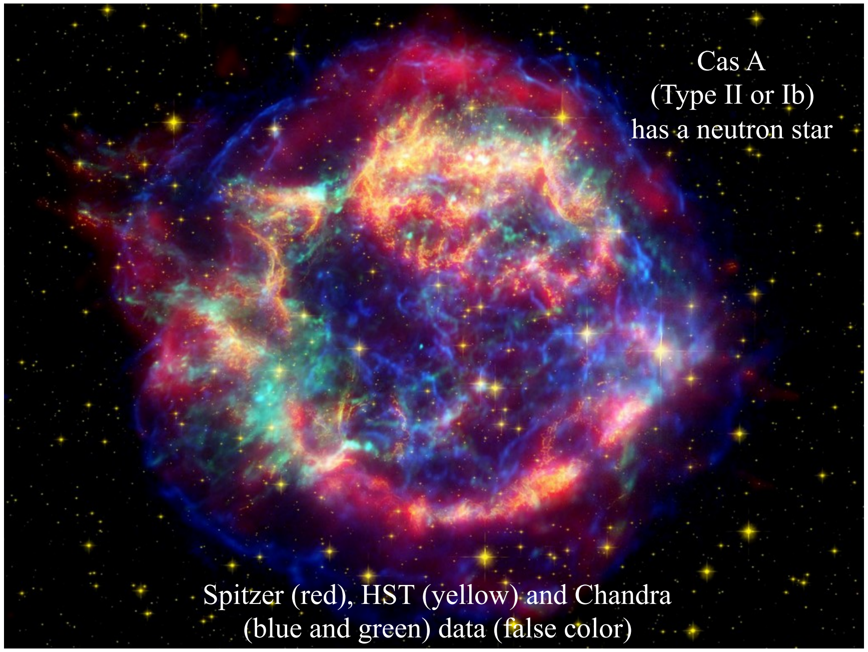
Kepler’ s supernova remnant in the optical (HST yellow),
IR (Spitzer (red), and x-ray (Chandra, blue and green).
Blue and yellow are shocked gas, green is hot gas, red is dust.

http://chandra.harvard.edu/photo/



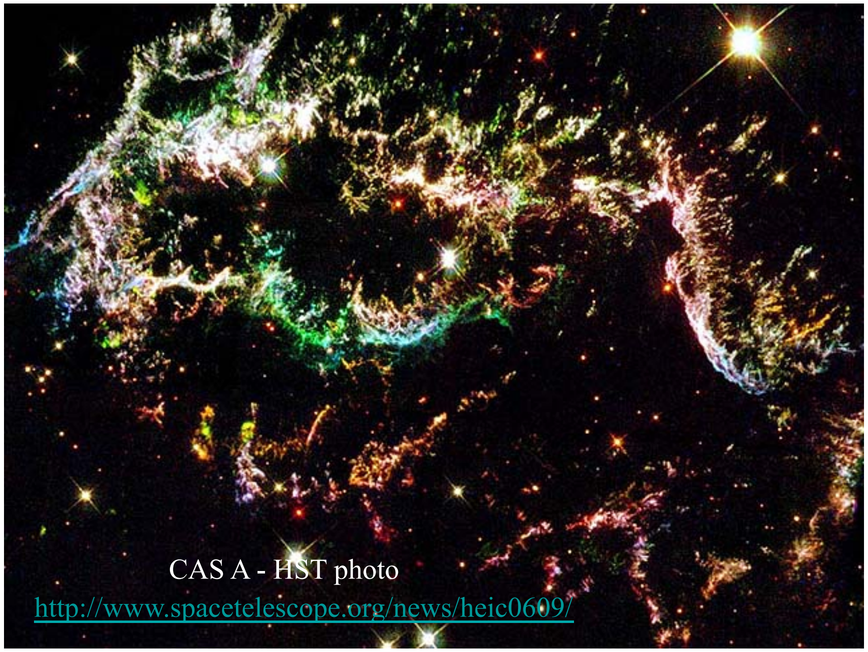
Last SN seen(?)
in our galaxy

Cassiopeia A (*aka* Cas A) is the remnant of an optically faint supernova (about m = 6) perhaps observed by John Flamsteed in 1680. It is 3.4 kpc away and 10 ly in diameter. This is a color coded x-ray photo by the Chandra X-Ray Astronomy Observatory taken in 1999. Red is about 20 million K; blue about 30 million K. Spectroscopy shows prominent lines of Fe, Si, O, S. Fe knots are found near the left outer boundary despite having been synthesized near the center. Brightest knots are Si, S.



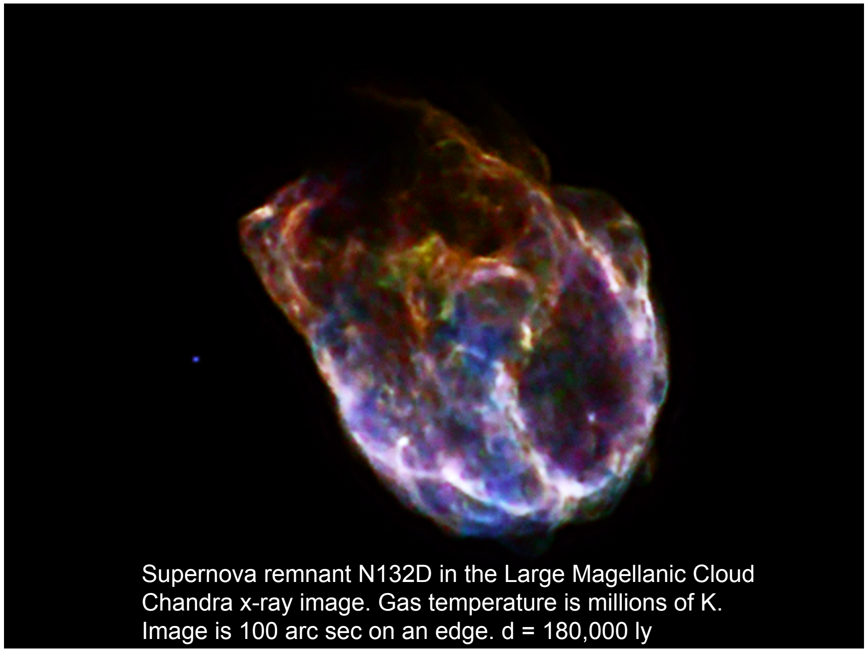
Cas A
(Type II or Ib)
has a neutron star

Spitzer (red), HST (yellow) and Chandra
(blue and green) data (false color)



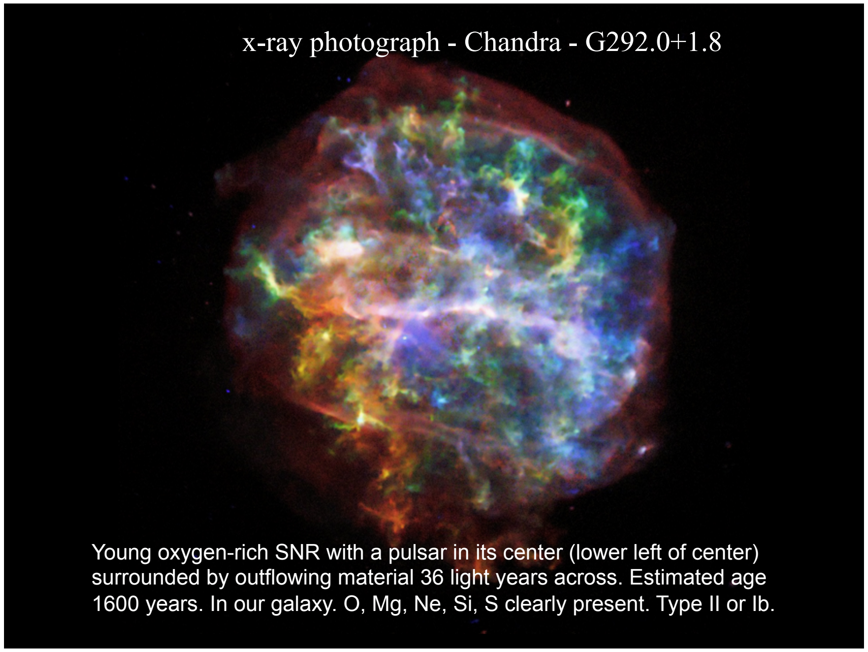
CAS A - HST photo

http://www.spacetelescope.org/news/heic0609/



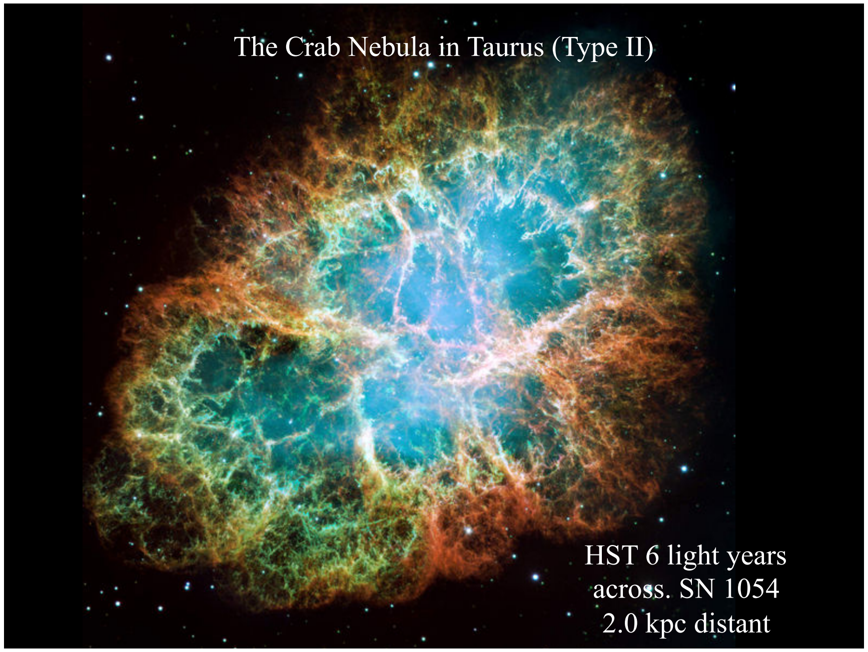
Supernova remnant N132D in the Large Magellanic Cloud
Chandra x-ray image. Gas temperature is millions of K.
Image is 100 arc sec on an edge. d = 180,000 ly

x-ray photograph - Chandra - G292.0+1.8



Young oxygen-rich SNR with a pulsar in its center (lower left of center) surrounded by outflowing material 36 light years across. Estimated age 1600 years. In our galaxy. O, Mg, Ne, Si, S clearly present. Type II or Ib.

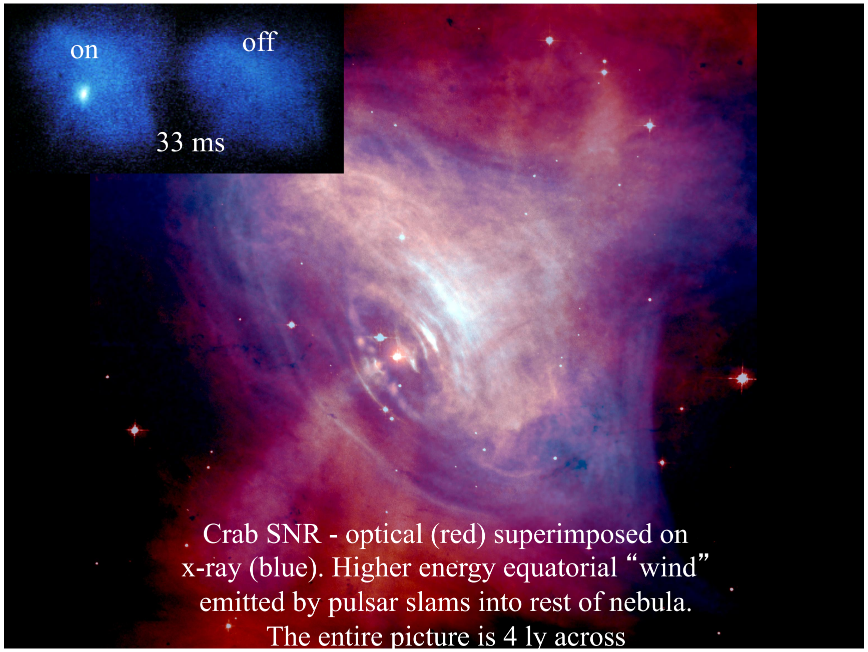
The Crab Nebula in Taurus (Type II)



HST 6 light years
across. SN 1054
2.0 kpc distant

SN 1054 (The Crab)

- Well observed by Chinese astronomers
- Bright enough to be seen in daylight for 23 days. Bright enough to cast a shadow.
- Visible in the night sky for 653 days
- 6300 ly distant
- May also have been seen by Anasazi and Irish. No conclusive European sightings (“Dark Ages”). Maybe records were lost.



Crab SNR - optical (red) superimposed on x-ray (blue). Higher energy equatorial “wind” emitted by pulsar slams into rest of nebula. The entire picture is 4 ly across

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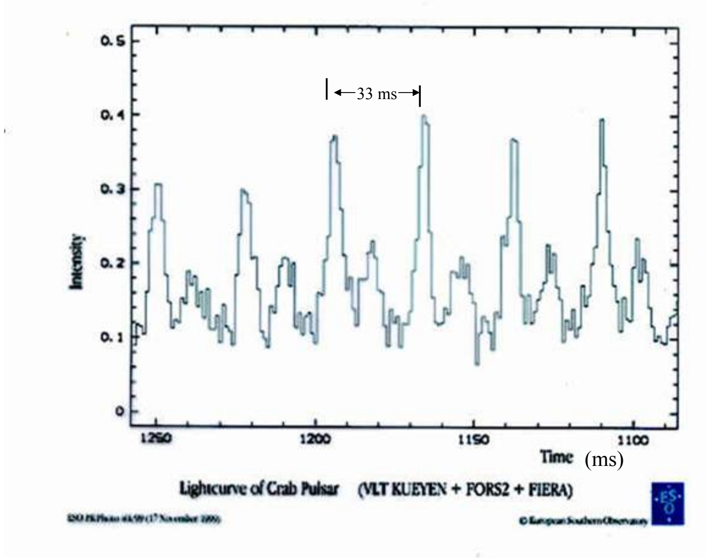
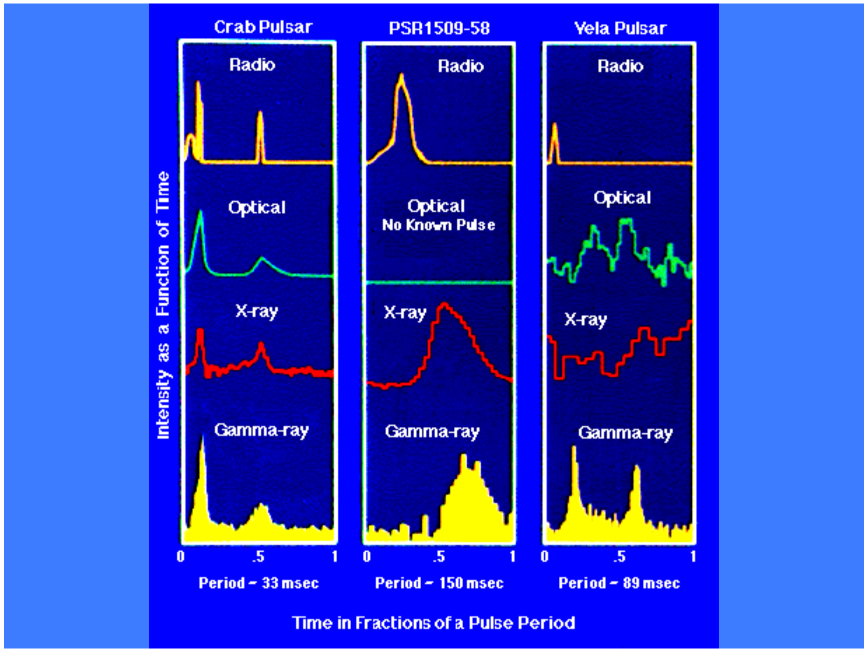
Pulsars and Neutron Stars



Lightcurve of Crab Pulsar (VLT KUEYEN + FORS2 + FIERA)



PULSARS

discovered in radio by Jocelyn Bell and Antony Hewish in 1967. Nobel Prize 1974

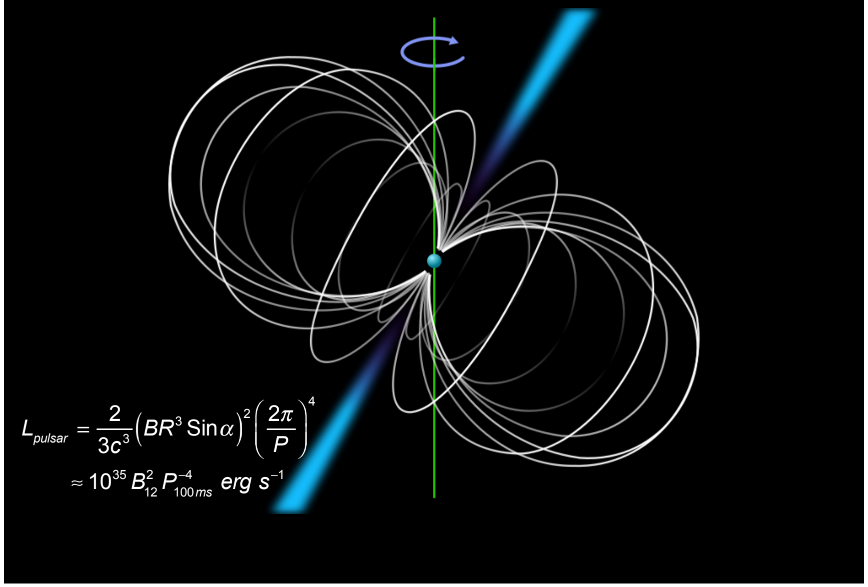
- Are rotating magnetic neutron stars with their rotational and magnetic axes not aligned. B ~ few x10^{12} Gauss (average sun 100 Gauss; sunspot ~ 1000 Gauss; Earth ~1 Gauss)

- Over 1000 now known. Periods range from about 1 ms to over 5 seconds. Accurate clocks (16 decimal places). Concentrated towards Galactic disk. Gradually slowing.

- Evidence for high "peculiar" velocities of typically several hundred km s^{-1}. May get "kicked" in the explosion. Many leave the galaxy.

- Some evidence they turn off after ~ 10^7 years due to magnetic field decay and spin down. Total number of neutron stars in the galaxy is about 10^8

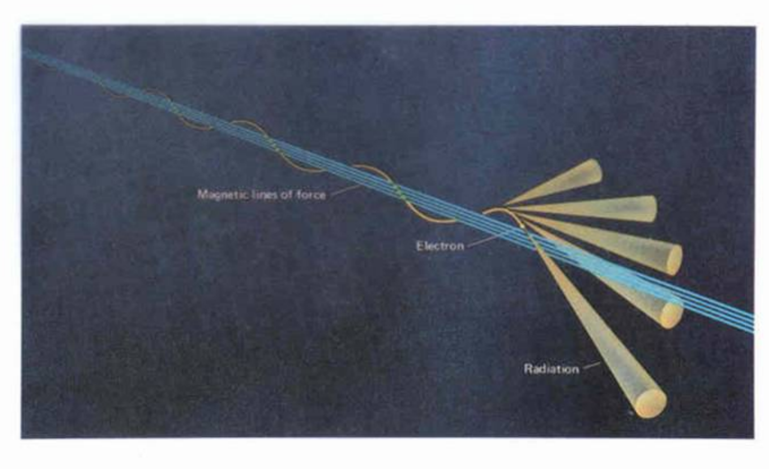
PULSAR



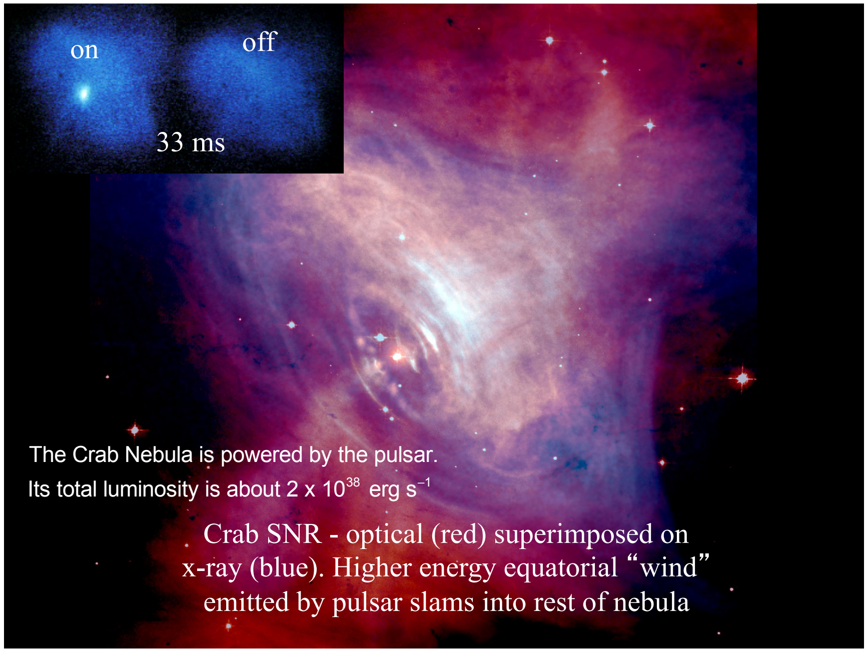
$$L_{pulsar} = \frac{2}{3c^3}\left(BR^3 \operatorname{Sin}\alpha\right)^2\left(\frac{2\pi}{P}\right)^4$$

$$\approx 10^{35} B_{12}^2 P_{100ms}^{-4}\ erg\ s^{-1}$$

SYNCHROTRON RADIATION



The radiation is not emitted to all angles in the sky but is "beamed" along a cone.



The Crab Nebula is powered by the pulsar.
Its total luminosity is about 2 x 10^{38} erg s^{-1}

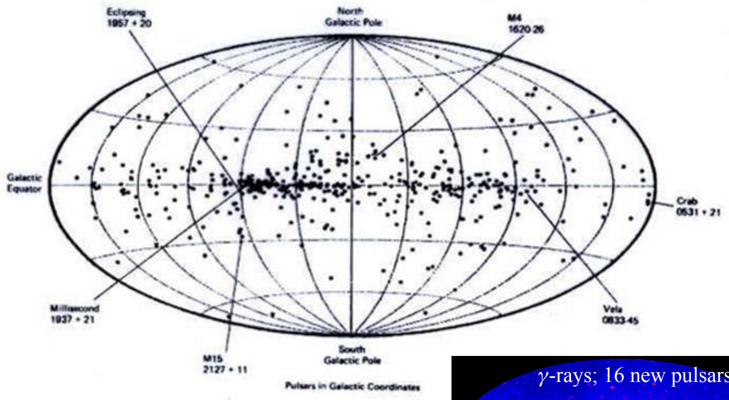
Crab SNR - optical (red) superimposed on x-ray (blue). Higher energy equatorial “wind” emitted by pulsar slams into rest of nebula

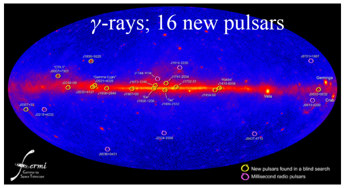
The Crab Nebula is powered by the pulsar.
Its total luminosity is about 2 x 10^{38} erg s^{-1}

The neutron star has a diple field strength of 5 x 10^{12} Gauss and it has a period of 33 ms so our formula gives

$$L \approx 10^{35}\, B_{12}^{2}\, P_{100ms}^{-4}\ erg\ s^{-1}$$

$$= 10^{35}\ 5^{2}\ \left(0.33\right)^{-4} = 2\times 10^{38}\ \text{erg s}^{-1}$$





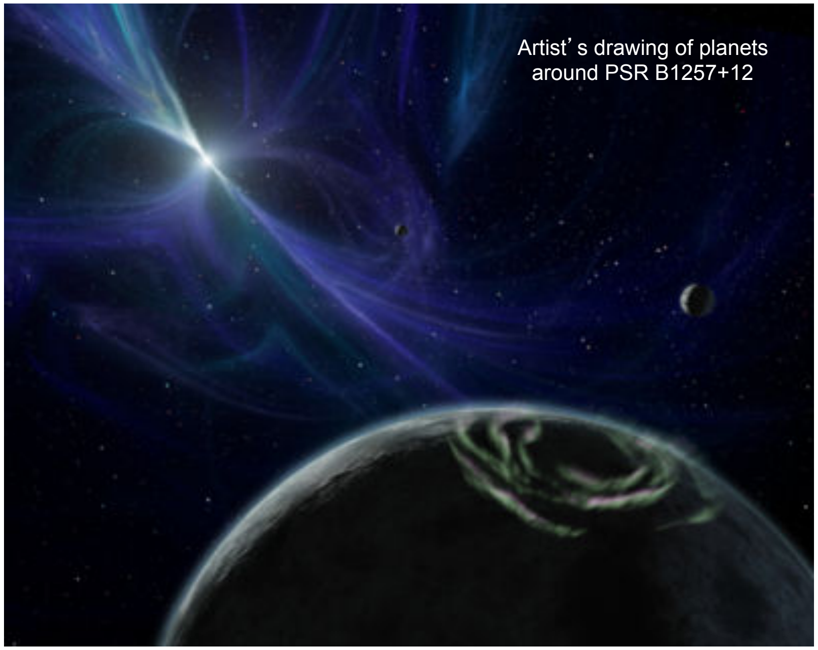
Listen to pulsars:

http://csep10.phys.utk.edu/astr162/lect/pulsars/pulsars.html

PULSARS (continued)

- Occasionally experience abrupt changes in period due to “starquakes”
- Emit pulsed radiation at all wavelengths. Not blackbody emitters.
- Spin down rates for solitary neutron stars in supernova remnants are thousands of years, consistent with the ages of the remnants in which they are found
- Most rapid rotators in mass exchanging binaries – probably spun up.
- Sometimes in binaries with other pulsars, white dwarfs or black holes - and even a planet

http://www.astro.psu.edu/users/alex/pulsar_planets_text.html

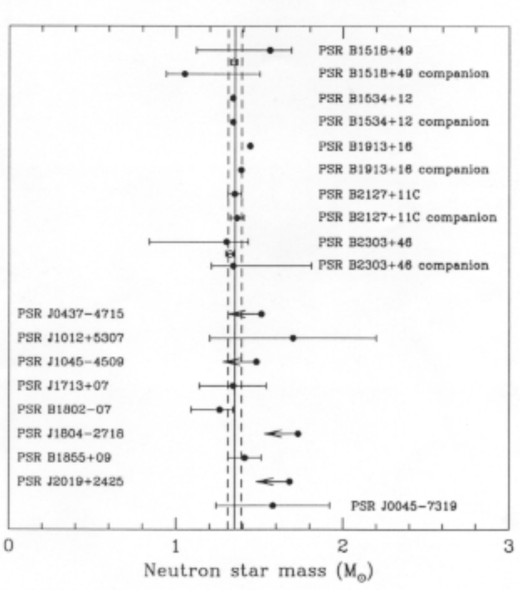


Artist' s drawing of planets around PSR B1257+12

The Pulsar B 1257+12 planetary system

Companion	Mass (Earths)	semimajor axis (AU)	Orbital period (d)	Eccentricity	Radius
A	.02+-.002	.19	25	0	-
B	4.3 +- .2	.36	66	0.0186	-
C	3.9+-.2	.46	98	0.0252	-
D	.0004	2.6	1250		-

Thorsett and Chakrabarty, (1999)



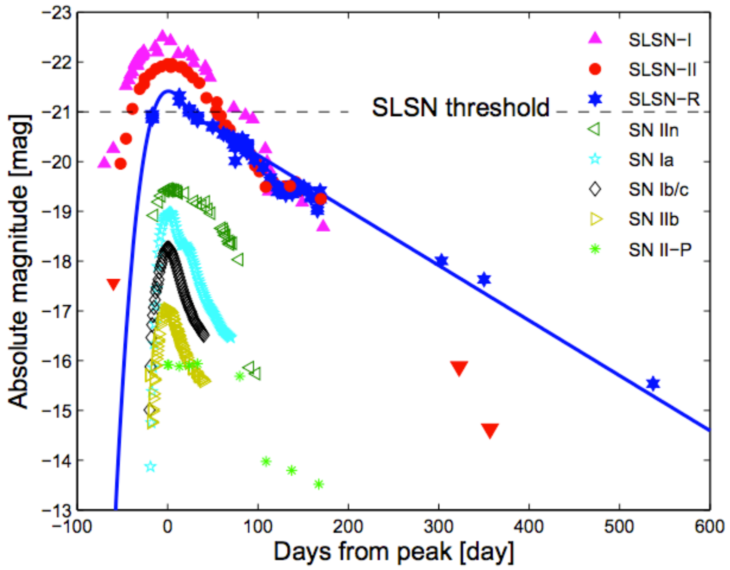
Vertical line is at 1.35 ± 0.04 $M_\odot$

Note that the iron core that collapsed had ~20% more mass

Ransom et al., *Science*, **307**, 892, (2005) find compelling evidence for a 1.68 solar mass neutron star in Terzian 5

More recently (Oct 28, 2010 Nature) Demorest et al find a 1.97 solar mass neutron star in a binary system where the mass could be accurately determined.

Unusually Bright Supernovae from Massive Stars



Pair-instability Supernovae

A simple way to make a supernova, without neutrinos, neutron star formation, etc, but it requires a very massive star

Consider a helium core of 100 $M_\odot$ or so. This might require a main sequence star of 150 - 200 $M_\odot$.

early universe?

More massive stars have higher temperatures and lower densities which favor radiation pressure and, as it turns out, the formation of electron positron pairs after carbon ignites.

$$\gamma \rightleftharpoons e^+ + e^- \qquad T > 10^9 \text{ K}$$

but it takes energy to create the rest masses of the electron and a positron, so for awhile, contraction doesn't lead to as much pressure increase as it would have. In fact P $\propto \rho^n$ with n <4/3. The star is unstable.

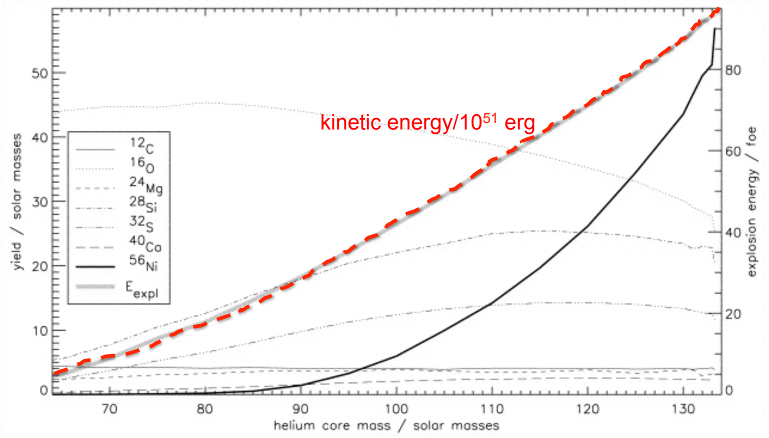
Pair-instability Supernovae

The star's core collapses and gets hotter and then burns oxygen and, in some cases silicon explosively. The energy release from the implosion can - for a range of masses - turn the collapse into a thermonuclear explosion, a *pair - instability supernova.* So much burning goes on that these can be very energetic.

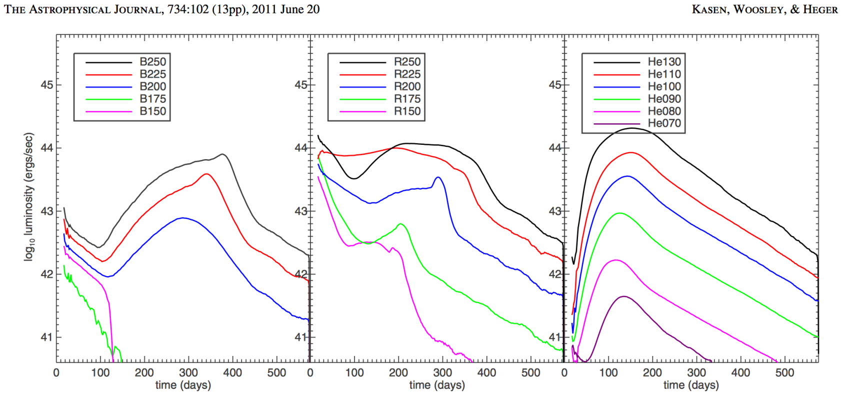
Helium core mass (M_{sun})	Outcome
< 35	Stable
35 to 65	Pulses violently, colliding shells may make multiple supernovae
65 to 133	Complete explosion of the star. Nothing left. Can be very bright
> 133	Collapses directly to a black hole

!

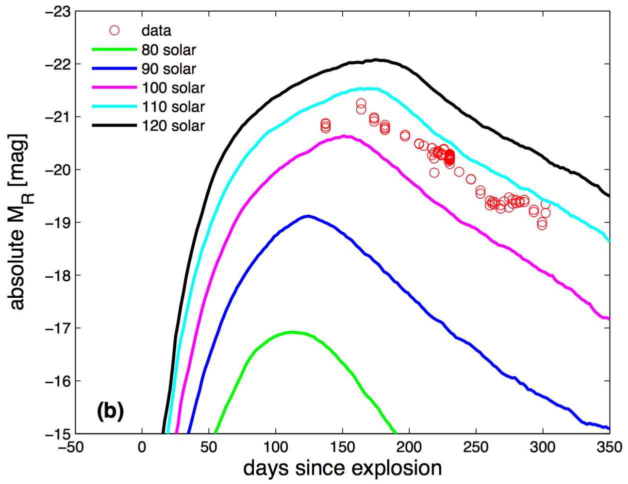
Pair-instability Supernovae



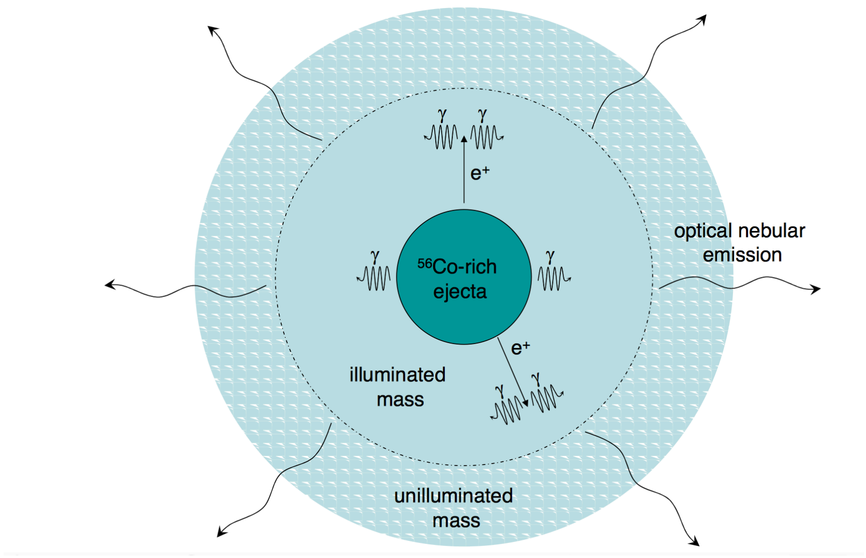
kinetic energy/10^{51} erg

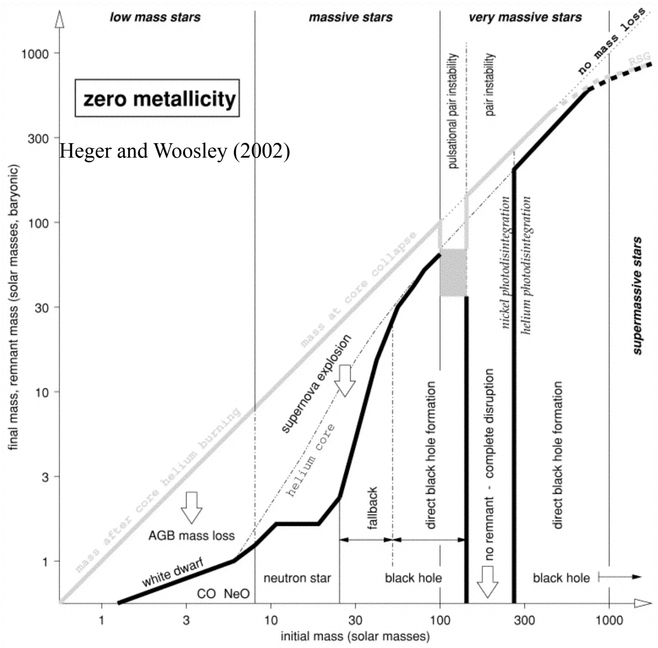


The Astrophysical Journal, 734:102 (13pp), 2011 June 20 — Kasen, Woosley, & Heger

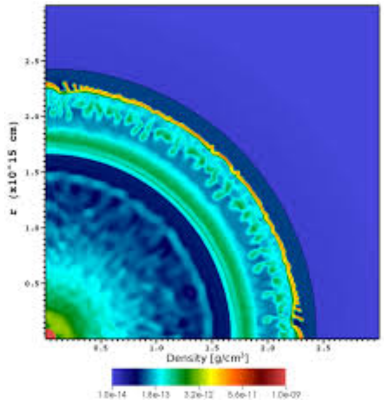


SN 2008bi - GalYam et al, Nature, (2009) reported as a pair-instability supernova. Data compared with models by Kasen, Woosley and Heger (2002, 2008)





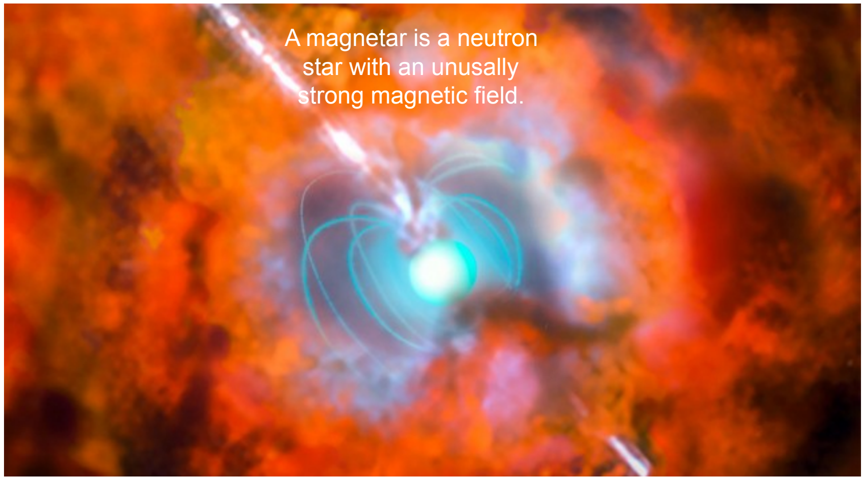
Heger and Woosley (2002)



“Colliding shells” are also an efficient way of making a very luminous supernova.

If a supernova explodes after having recently ejected a lot of mater, then the shock wave where the two set of ejecta collide can be very luminous.

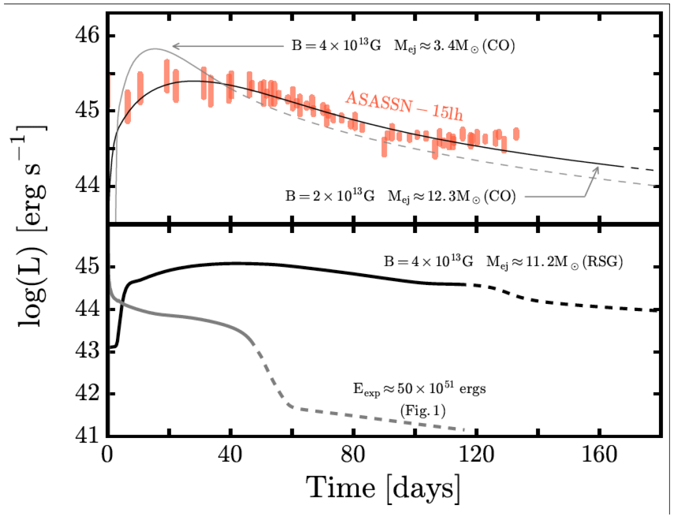
Up to 10^{44} erg s^{-1} and maybe more.


A magnetar is a neutron star with an unusally strong magnetic field.

$$\frac{dE}{dt} = \frac{2}{3c^3}\left(BR^3\ \mathrm{Sin}\,\alpha\right)^2\left(\frac{2\pi}{\mathrm{P}}\right)^4$$
$$\approx 10^{49} B_{15}^2 \mathrm{P}_{\mathrm{ms}}^{-4}\ \mathrm{erg\ s}^{-1}.$$

$$B_{15} = \frac{B}{10^{15}\ \mathrm{Gauss}}$$

Woosley (2010)



Brightest SN ever!! Model by Sukhbold and Woosley (2016)