Binary Evolution
Novae, Supernovae, and X-ray Sources

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

http://www.space.com/32150-farthest-galaxy-smashes-cosmic-distance-record.html

The Algol Mystery

- Algol is a double-lined eclipsing binary system with a period of about 3 days (very short). The two stars are:

  Star A: B8, 3.4M_o main-sequence star

  Star B: G5, 0.8M_o \`subgiant' star

What is wrong with this picture?

(very short period is a clue)

Algol

- The more massive star (A) should have left the main sequence and started up the RGB before the less massive star (B).
- What is going on here?
- The key is the short-period orbit and the evolved state of star B.

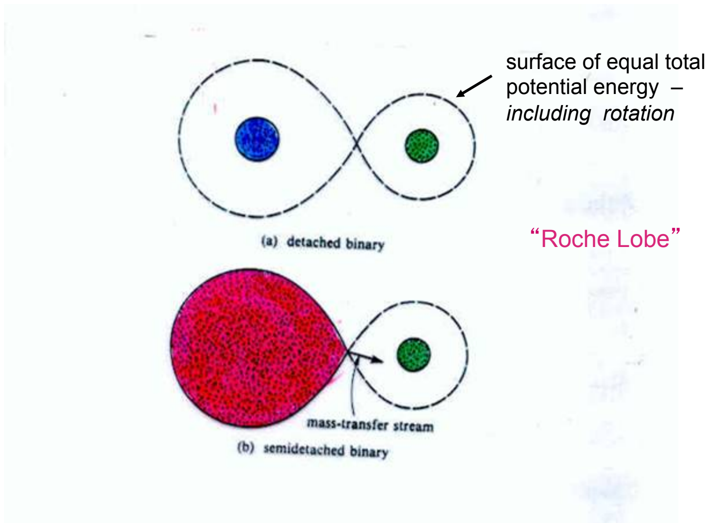
Mass Transfer in Binaries

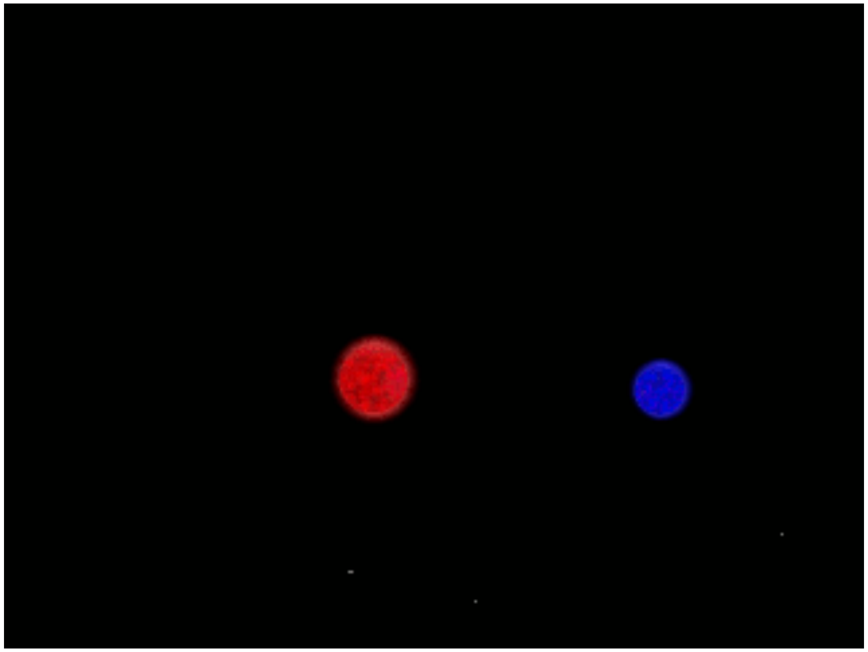
- In the case of Algol, Star B, which initially had a mass of 3.0 M_o transferred 2.2M_o of material to Star A, which initially was 1.2 M_o, after it became a red giant.

Star A: 1.2M_o -> 3.4M_o (main sequence)

Star B: 3.0M_o -> 0.8M_o (red giant)

Binary Star Evolution





Mass exchange can greatly alter stellar evolution. It can change the composition we see on the surface of a star and can alter the lifetime and luminosity of both stars. Also …

- When a massive star becomes a red giant, it may spill its H-envelope onto its companion changing the evolution of both. E.g.

  Type Ib supernova

- After the (initially) more massive star has died, interesting systems can be created in which one "star" is a white dwarf, neutron star, or black hole, with another more ordinary star spilling matter onto it.

  Classical novae
  Type Ia supernovae
  X-ray binaries

CLASSICAL NOVAE

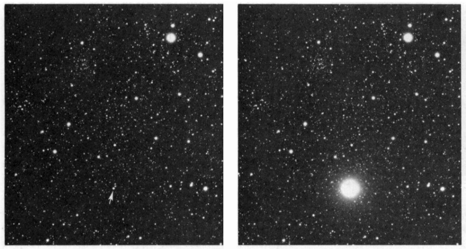
- Classical novae are thought to occur about 30 to 60 times a year in the Milky Way, but only about 10 are discovered each year.

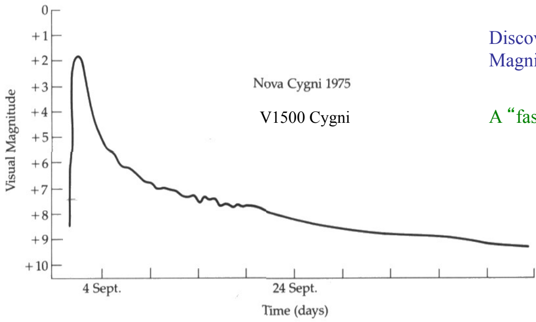
- L ~ 10^{38} erg s^{-1} for several days to months. About 10^5 times the luminosity of the sun, but ~10^5 times less luminous than the brightest supernova, but 10^5 more luminous than the sun

- Recur – in theory - but the recurrence time scale may be very long - typically tens of thousands of years

- Some mass is ejected, but the amount is small 10^{-6} - 10^{-4} solar masses. The velocities are slower than supernovae – 100's to perhaps 1000 km s^{-1}

- Show emission lines of H, He, C, N, O, Ne, and Mg





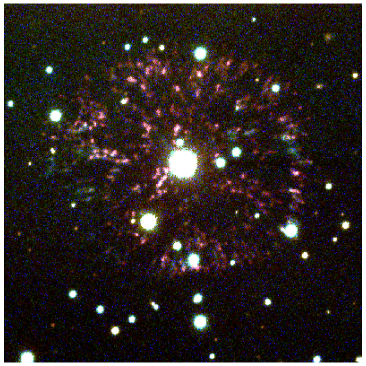
Discovery Aug 29, 1975
Magnitude 3.0

A "fast" nova

Novae

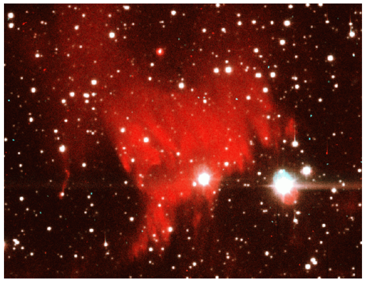
- Nova Vel 1998 (3rd magnitude)

Novae



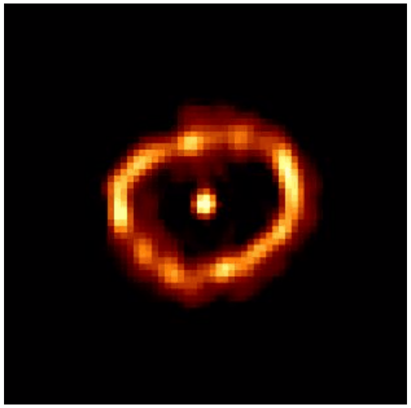
- Nova Persei became one of the brightest stars in the sky in 1901. Look there now and see the expanding shell from the explosion. The velocity of the material is ~2000km s^{-1}

Novae



- Nova Cyg (1992) illuminated a cloud of nearby Hydrogen gas.
- The expanding shell of the nova could be seen a few years later with HST.

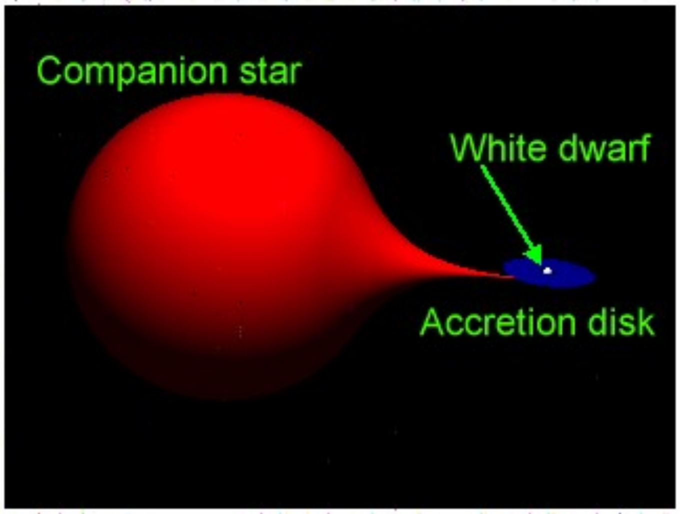
Nova Cygni 1992



Visible magnitude at peak was 4.3. Photo at left is from HST in 1994. Discovered Feb. 19, 1992. Spectrum showed evidence for ejection of large amounts of neon, oxygen, and magnesium.

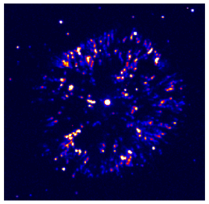
"Naked eye" novae occur roughly once per decade.

2.5 light days across
ejected mass ~2×10^{-4} solar masses

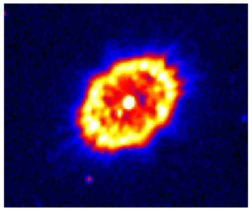


The companion star is typically a low mass (K or M) main sequence star. The orbital period is short < 1 day.

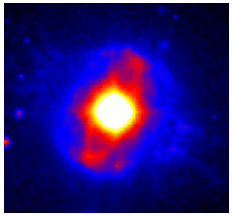
An earth mass or so is ejected at speeds of 100s to 1000s of km s^{-1}. Years later the ejected shells are still visible. The next page shows images from a ground-based optical survey between 1993 and 1995 at the William Hershel Telescope and the Anglo-Australian Telescope.



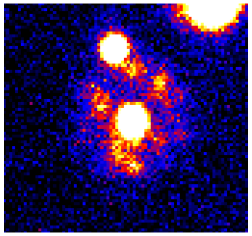
Nova Persei (1901)
GK Per



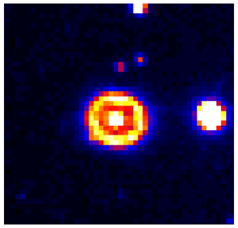
Nova Hercules (1934)
DQ - Her



Nova Pictoris (1927)
RR Pic



Nova Cygni (1975)
V1500 Cygni



Nova Serpentis (1970)
FH Ser

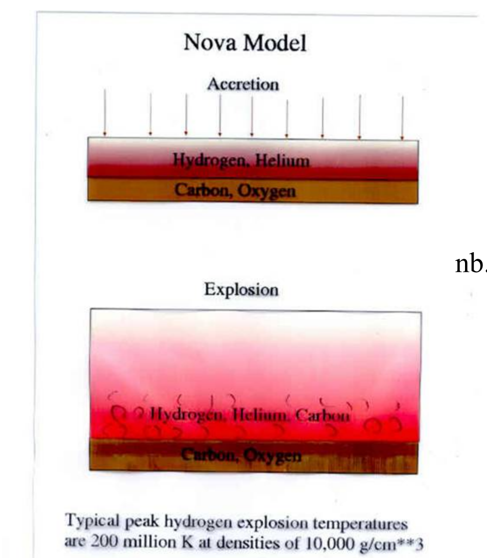
http://www.jb.man.ac.uk/~tob/novae/

MODEL FOR CLASSICAL NOVAE

- A carbon-oxygen white dwarf accretes at a slow rate of about 10^{-10} - 10^{-8} solar masses per year from a binary companion. Hydrogen and helium accumulate on the surface (at higher accretion rates can get SN Ia).

- This material is initially too cool for nuclear reactions, but as accretion continues, it is compressed and heated. At about 10^4 g cm^{-3}, hydrogen burning ignites ("hot" CNO cycle; temperature over 100 Million K)

- Inititially the material is degenerate. Burning is also unstable because it happens in a thin shell on the WD surface. Hydrogen burns explosively. Not all of the hydrogen burns because the material is not very tightly bound to the white dwarf, but it all is ejected



nb. Novae can *repeat!*

accrete
explode
accrete
explode
.
.
.

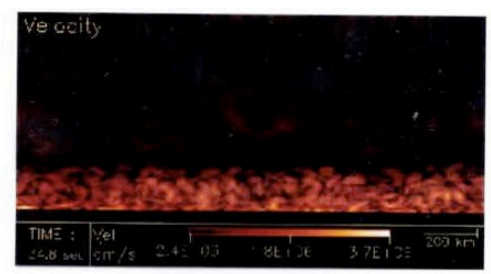
Binding energy per gm for a 1 $M_\odot$ white dwarf

$$\frac{GM}{R} = \left(\frac{(6.67\times10^{-8})(2\times10^{33})}{5\times10^{8}}\right)$$

$$\approx 3\times10^{17}\ \text{erg g}^{-1} \ll 6.8\times10^{18}\ \text{erg g}^{-1} = q_H$$

- The hydrogen continues to burn for several months as the entire accreted layer is driven off the star in a powerful wind. None of the accreted material is left behind.

- Accretion then resumes and the cycle repeats

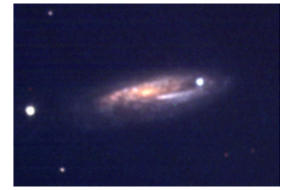


Kercek et al (1999)

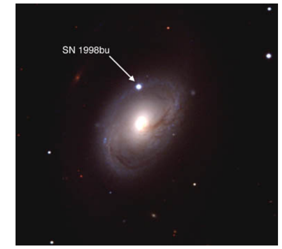
About
5000 trillion
megatons/sec

Type Ia Supernovae

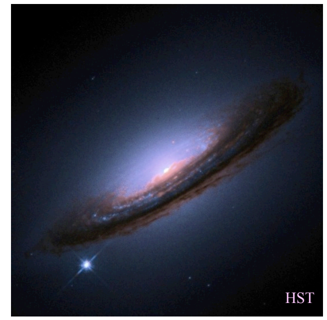
SN 1998aq



SN 1998dh



SN 1998bu



SN 1994D

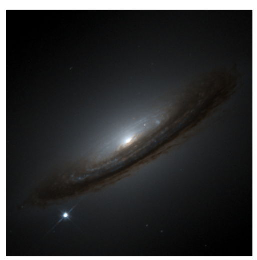
Type Ia supernovae are some of the biggest thermonuclear explosions in the universe (only pair-instability SN are bigger).

Thirty billion, billion, billion megatons.

For several weeks their luminosity rivals that of a large galaxy.

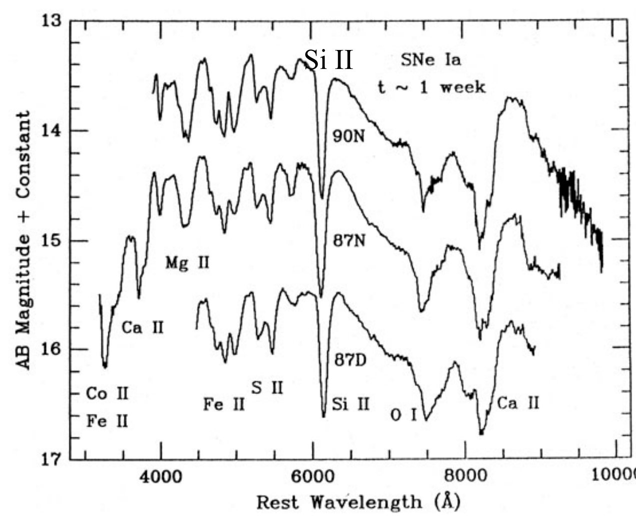
Observational facts

- Very bright, regular events, peak $L \sim 10^{43}$ erg s^{-1}
- Associated with an old stellar population (found in ellipticals, no clear association with spiral arms when in spiral galaxies)
- No hydrogen in spectra; strong lines of Si, Ca, Fe
- Total kinetic energy $\sim 10^{51}$ erg (nothing left behind)
- Higher speed, less frequent than Type II



SN 1994D

Spectra are similar from event to event



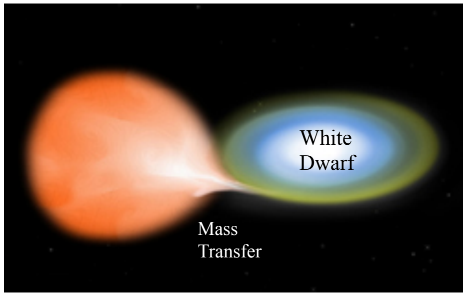
Spectra of three Type Ia supernovae near peak light – courtesy Alex Filippenko

Possible Type Ia Supernovae in Our Galaxy		
SN	D(kpc)	m_V
185	1.2+-0.2	-8+-2
1006	1.4+-0.3	-9+-1
1572	2.5+-0.5	-4.0+-0.3
1604	4.2+-0.8	-4.3+-0.3

Expected rate in the Milky Way Galaxy about 1 every 200 years, but dozens are found in other galaxies every year. About one SN Ia occurs per decade closer than 5 Mpc. SN 2014J was at 3.5 Mpc and is being extensively studied.

(A) A Leading Model*

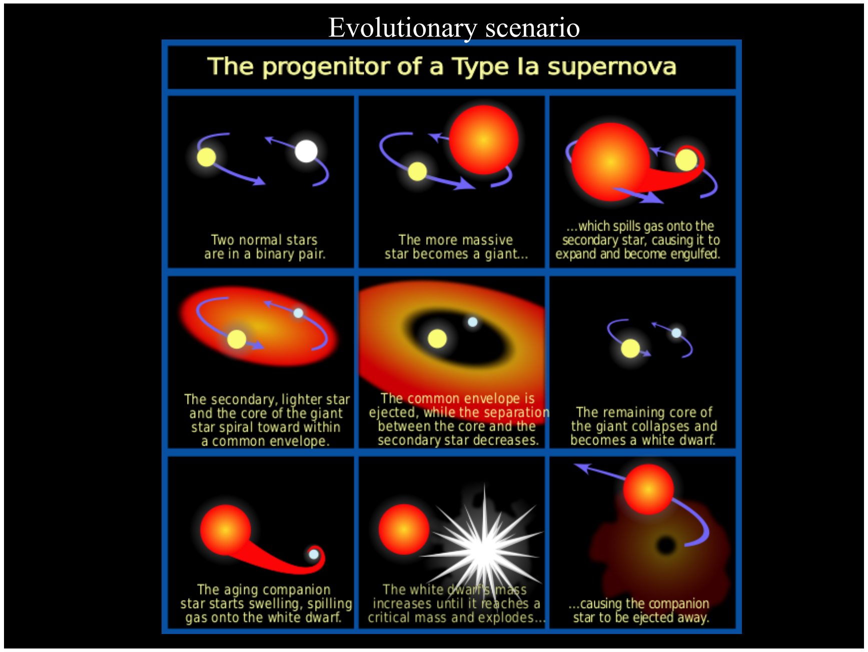
Accretion and growth to the Chandrasekhar Mass (1.38 solar masses)
Degenerate thermonuclear explosion. (Hoyle and Fowler, 1960).



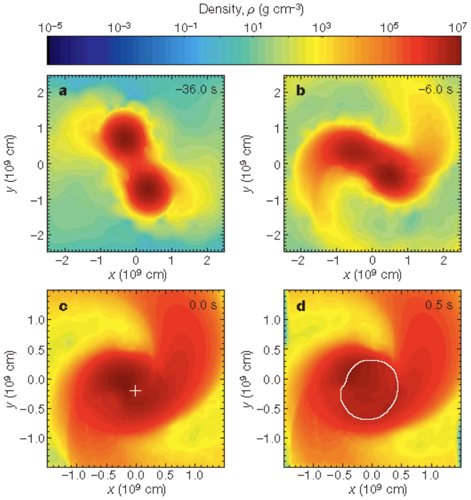
Explains:

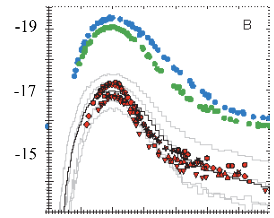
- Lack of H in spectrum
- Association with old population
- Regularity
- Large production of ^{56}Ni and a light curve dominated by radioactivity.

* there are 2 others a) merging white dwarfs and b) explosion well before the Chandrasekhar mass is reached.



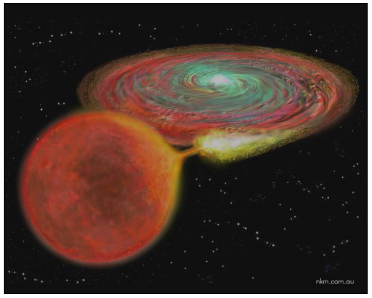
Another Possibility
Merging White Dwarfs





0.9 + 0.9 solar mass WD still make subluminous event

1.1 + 0.9 can make a more typical SN Ia like 2011fe (Roepke et al 2012, ApJL, 750, L19)



In order for the white dwarf to grow and reach the Chandrasekhar Mass the accretion rate must be relatively high (to avoid the nova instability). In the case of the "single degenerate model" this must be maintained for millions of years.

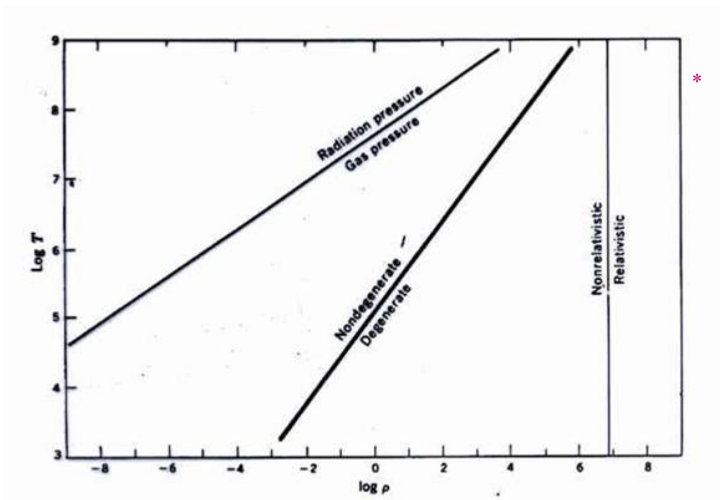
$$\dot{M} \sim 10^{-7} M_{sun} / yr$$

Progenitor

Ignition occurs carbon fusion in the center of the white dwarf begin to generate energy faster than convection and neutrino losses can carry it away.

$$\text{As } \rho \rightarrow 2\,x\,10^{9} \text{ gm cm}^{-3};\ \text{T} \approx 3\,x\,10^{8} \text{ K}$$

$$M \approx 1.38\, M_{\odot}$$

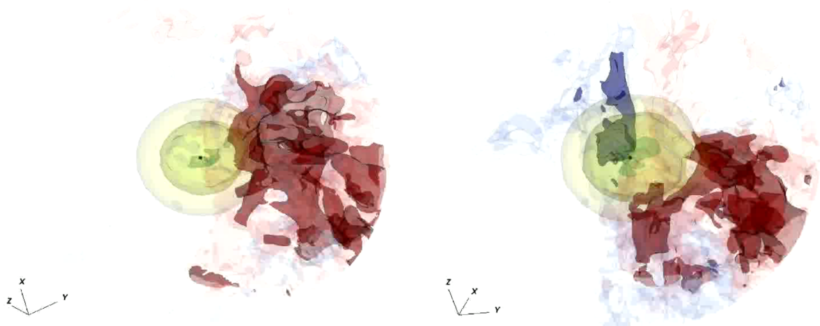


P is independent of T, but $\varepsilon_{nuc} \propto T^{26}$ for carbon burning $\Rightarrow$ BANG

Ignition at $\rho_c \sim 3 \times 10^9$ because:

1) Neutrino loss rates decline at very high density
2) Carbon fusion reaction enhanced at high density by "electron screening"
3) Central regions compressed and heated by accretion of matter on surface.

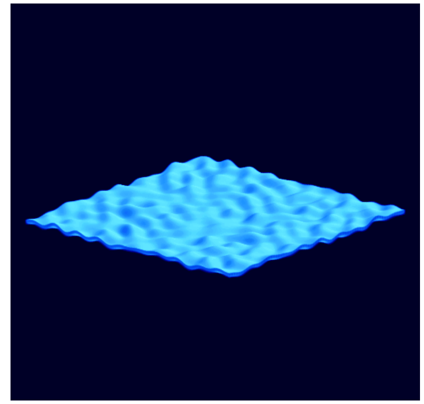
Once carbon ignites, the core begins to convect. Energy is generated too fast for conduction or diffusion to get it to the surface fast enough.

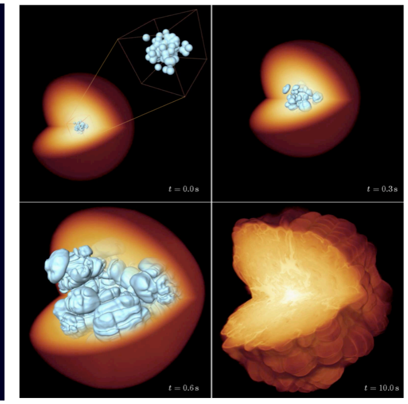


MAESTRO simulations of convection in a non-rotating white dwarf (left) and a 1.5% Keplerian rotating white dwarf (right) preceding a Type Ia supernova. Each simulation uses adaptive mesh refinement with an effective 768^3 zones (6.5 km spatial resolution)

Explosion preceded by about a century of convection. The convection is asymmetric

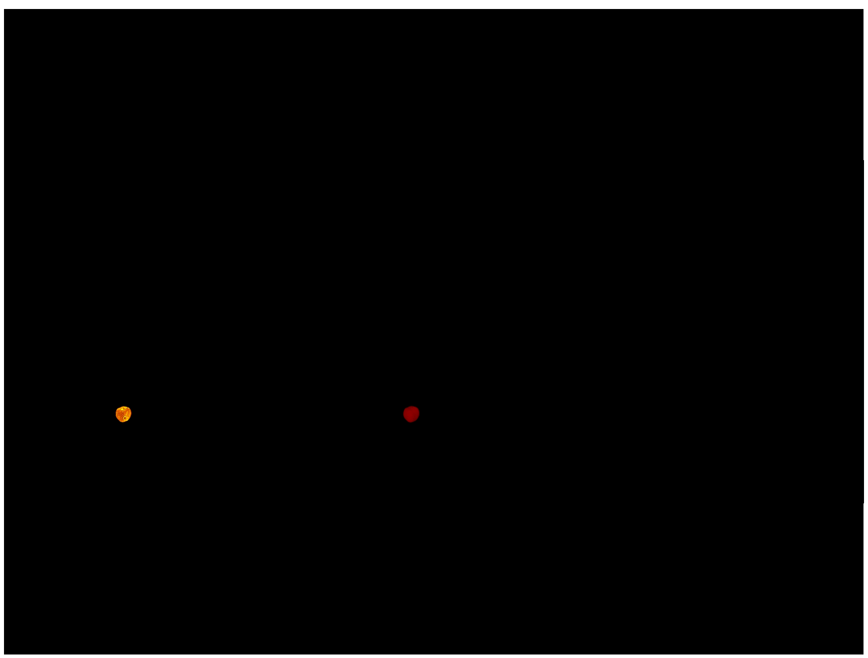
The Explosion - Burning and Propagation

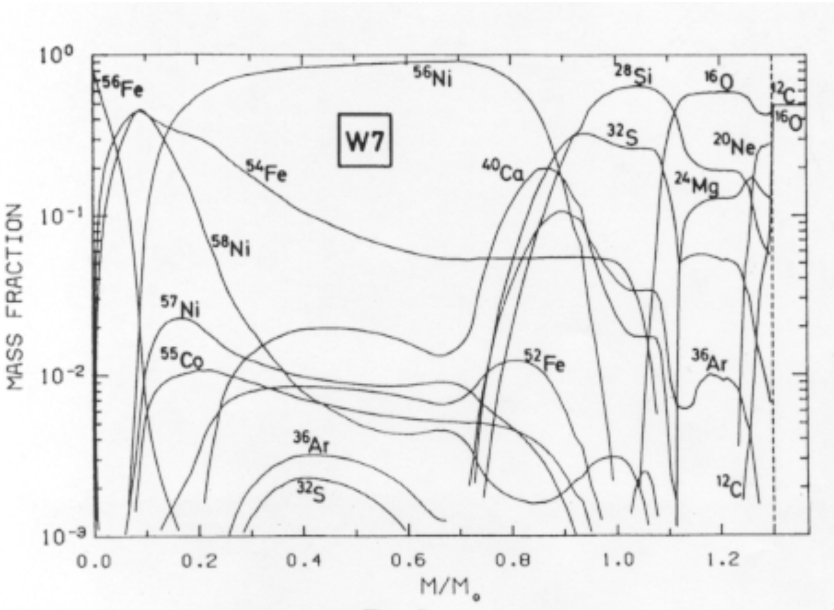


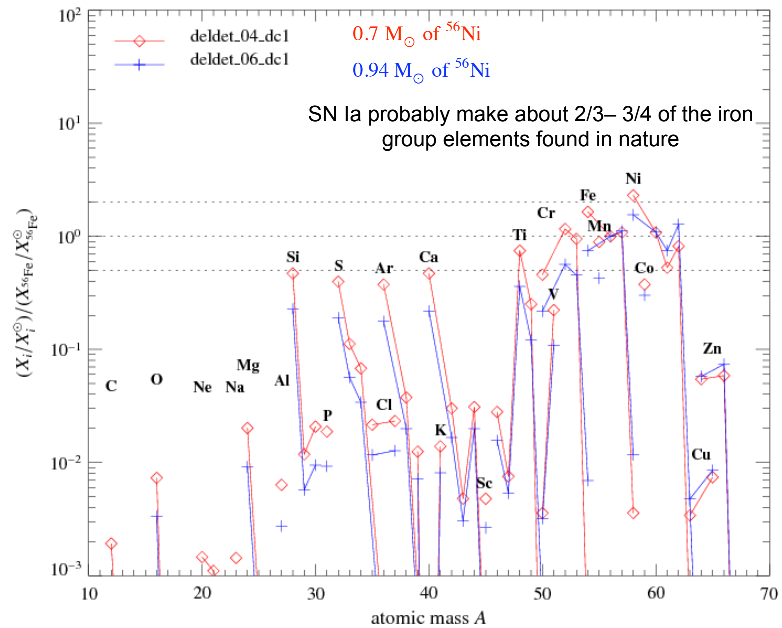


Zingale et al. (2005)

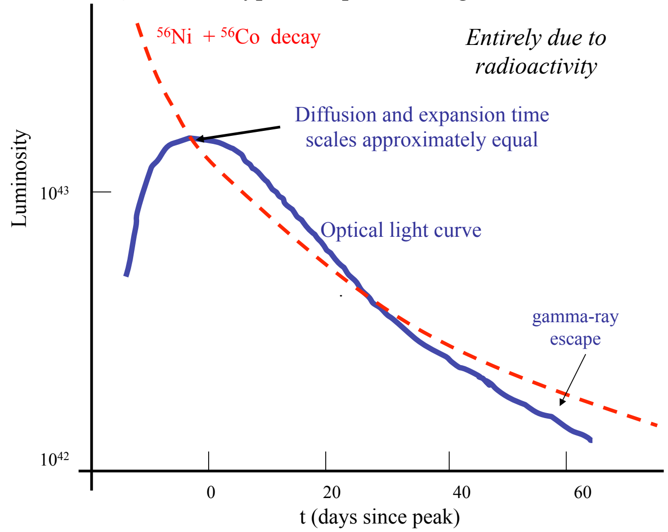
Roepke and Hillebrandt (2007)







Qualitative Type Ia Supernova Light Curve



Radioactivity

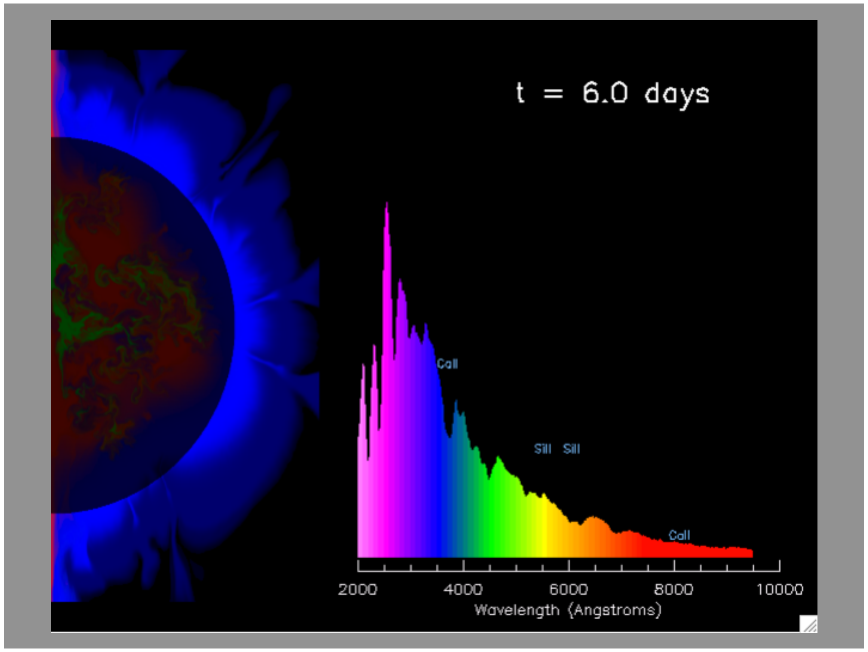
$$^{56}\text{Ni} + e^- \rightarrow {}^{56}\text{Co} + \nu \qquad \tau_{1/2} = 6.1 \text{ days}$$

$q = 3.0 \times 10^{16}$ erg/gm

$$^{56}\text{Co} + e^- \rightarrow {}^{56}\text{Fe} + \nu \qquad \tau_{1/2} = 77.1 \text{ days}$$

$q = 6.4 \times 10^{16}$ erg/gm

0.6 solar masses of radioactive Ni and Co can thus provide 1.1×10^{50} erg at late times after adiabatic expansion is essentially over.



Supernova

(Death of a star)

Type Ia

- 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

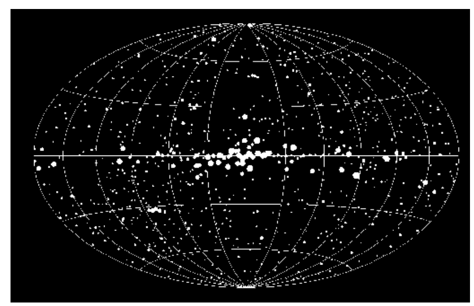
- Hydrogen in spectrum
- M > 8 solar masses
- Iron core collapses to a neutron star or black hole
- ~10^{51} erg kinetic energy
- v ~ 2,000 – 30,000 km s^{-1}
- Neutrino burst ~ 3 x 10^{53} erg
- $E_{optical}$ ~ 10^{49} erg
- L_{peak} ~ 3 x 10^{42} erg s^{-1} for about 3 months (varies from event to 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

Binary X-Ray Sources

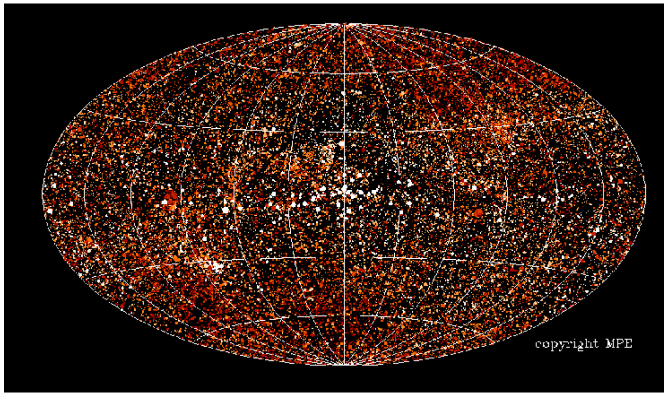
A neutron star or black hole receiving mass from a companion star

The bright x-ray sky – mostly point sources (AGN, SNR, black holes and neutron stars)



HEAO survey completed 1978
841 sources mostly binary systems containing a neutron star or a black hole.

Also Giacconni - rockets in 60's
UHURU = SAS 1 1970 - 1973



ROSAT – first pass in 1990 – 1991 50,000 sources. By 1999 over 150,000 sources had been catalogued. Many are "normal stars".

red > 100,000 K
white ~ 20 million K

luminosities ~ 10^{36} - 10^{38} erg s^{-1}

X Ray Binaries

- Two classes based upon mass of companion star that is feeding the x-ray emitting compact object

- High mass donors (over about 5 solar masses) are found in the disk of the galaxy and are Population I. The donor star is typically a B-type main sequence star or a blue supergiant. Roughly 300 are estimated to exist in our galaxy. Lifetime < 10^8 years. Long period. High accretion rate. Visible far away. Dust extinction not a problem.

- Low mass x-ray binaries contain a donor star of < about 1 solar mass which may be a main sequence star. Population II. Found in Galactic center, globular clusters, in and above disk. Roughly 300 estimated to exist.

- Luminosities in X-rays for both are ~ 10^{36} – 10^{38} erg s^{-1}. Spectra are approximately black bodies – but x-rays means they are very hot ~10^7 K

MODELS

- The persistent emission of all x-ray binaries is due to the gravitational energy released by the accreted matter as it impacts the surface of the neutron star (black holes are a special case of this where the energy is released in a disk outside the event horizon).

- Typical accretion rates are 10^{-8} $M_\odot$ y^{-1} (or 6×10^{17} g s^{-1}

$$\dot{M} \equiv \frac{dM}{dt}$$

$$L = \frac{GM\dot{M}}{R} = \frac{(6.67\times10^{-8})(1.4)(2\times10^{33})(6\times10^{17})}{1.0\times10^{6}} = 1\times10^{38}\ \mathrm{erg\,s^{-1}}$$

- This is still approximately blackbody radiation, so

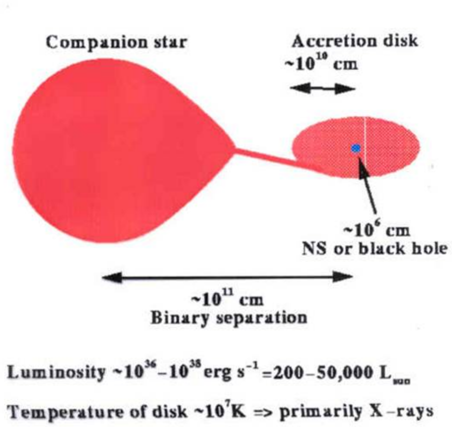
$$T_{eff} \approx \left(\frac{L}{4\pi R^2\sigma}\right)^{1/4} = 2\times10^7\ \mathrm{K}$$

$R \approx 10$ Km

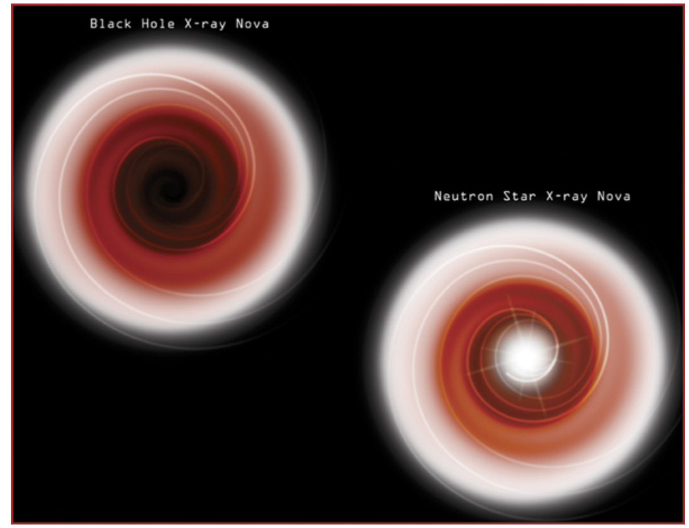
which corresponds to x-rays

$$\lambda_{max} = \frac{0.289\ \mathrm{cm}}{T_{eff}} = \frac{2.89\times10^7\ \mathrm{Angstroms}}{T_{eff}}$$
$$\approx 3\ \mathrm{Angstroms\ (X\text{-}rays)}$$

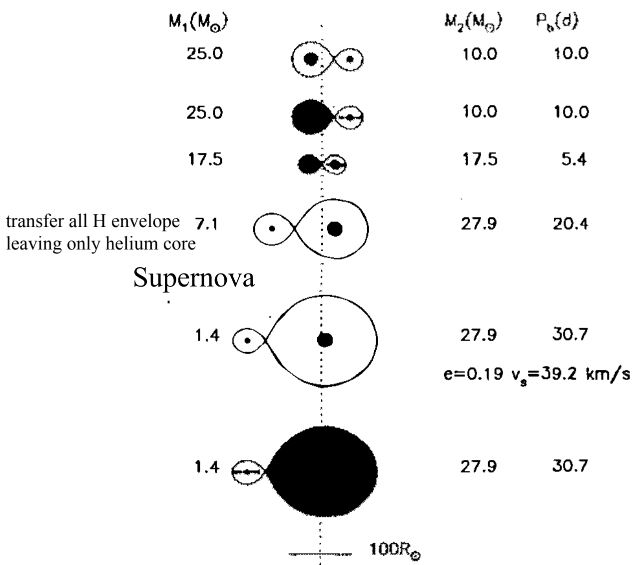
Accreting neutron star or black hole



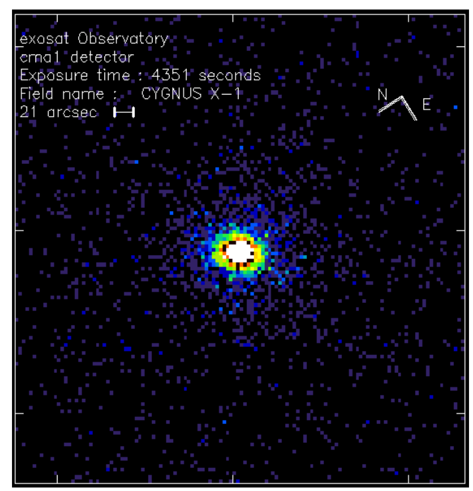
Black Hole Illustration



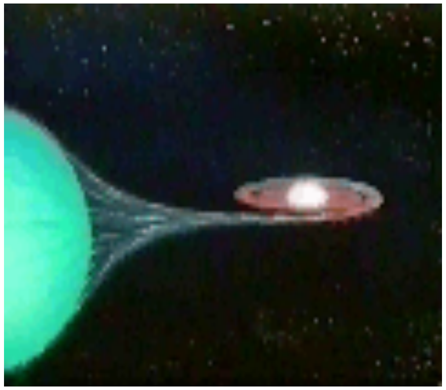
High Mass X-Ray Binary Formation



Cyg X-1 in X-Rays



Artist's Rendition of Cyg X-1



Discovered in early 1970's
Companion is a blue supergiant HDE226868
Period 5.6 days

Black hole candidates

Source	Companion	P (days)	Mass
Cygnus X-1	B supergiant	5.6	15
LMC X-3	main sequence	1.7	4-11
A0620-00 (V616 Mon)	K main sequence	7.8	4-9
GS2023+338 (V404 Cyg)	K main sequence	6.5	> 6
GS2000+25 (QZ Vul)	K main sequence	0.35	5-14
GS1124-683 (Nova Mus 1991)	K main sequence	0.43	4-6
GRO J1655-40 (Nova Sco 1994)	F main sequence	2.4	4-5
H1705-250 (Nova Oph 1977)	K main sequence	0.52	> 4
LMC X-1	post-main seq (32 M_0)	3.9	10.9

Fraknoi, Morrison, and Wolff p. 328

In the Milky Way….

Name	BHC Mass (solar masses)	Companion Mass (solar masses)	Orbital period (days)	Distance from Earth (light years)
A0620-00/V616 Mon	11 ± 2	2.6–2.8	0.33	about 3500
GRO J1655-40/V1033 Sco	6.3 ± 0.3	2.6–2.8	2.8	5000–11000
XTE J1118+480/KV UMa	6.8 ± 0.4	6–6.5	0.17	6200
Cyg X-1	11 ± 2	≥18	5.6	6000–8000
GRO J0422+32/V518 Per	4 ± 1	1.1	0.21	about 8500
GRO J1719-24	≥4.9	~1.6	possibly 0.6[15]	about 8500
GS 2000+25/QZ Vul	7.5 ± 0.3	4.9–5.1	0.35	about 8800
V404 Cyg	12 ± 2	6.0	6.5	7800 ± 460[16]
GX 339-4/V821 Ara		5–6	1.75	about 15000
GRS 1124-683/GU Mus	7.0 ± 0.6		0.43	about 17000
XTE J1550-564/V381 Nor	9.6 ± 1.2	6.0–7.5	1.5	about 17000
4U 1543-475/IL Lupi	9.4 ± 1.0	0.25	1.1	about 24000
XTE J1819-254/V4641 Sgr	7.1 ± 0.3	5–8	2.82	24000 – 40000[17]
GRS 1915+105/V1487 Aql	14 ± 4.0	~1	33.5	about 40000
XTE J1650-500	9.7 ± 1.6 [18]	.	0.32[19]	

Most companions are main sequence stars. Cygnus X-1 has a blue supergiant

https://en.wikipedia.org/wiki/Stellar_black_hole - Candidates

Most massive stellar mass black hole known M33 X-7 15.65 solar masses. Companion is also massive, about 70 solar masses

Period 3.45 days

3 Mly away

In the Triangulum galaxy

There are 26 BH candidates in Andromeda

https://en.wikipedia.org/wiki/M33_X-7
http://www.nasa.gov/mission_pages/chandra/news/bonanza.html