Binary Evolution
Novae, Supernovae, and X-ray Sources

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

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, $3.4 M_o$ main-sequence star
    Star B: G5, $0.8 M_o$ `subgiant' star
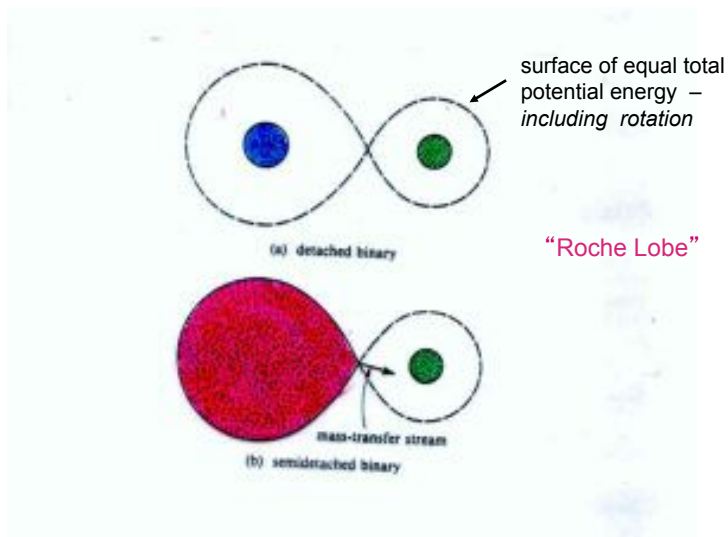
What is wrong with this picture?

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 transferred $2.2 M_o$ of material to Star A.

    Star A: $1.2 M_o$ -> $3.4 M_o$
    Star B: $3.0 M_o$ -> $0.8 M_o$

Binary Star Evolution

surface of equal total
potential energy –
including rotation

(a) detached binary

"Roche Lobe"

mass-transfer stream

(b) semidetached binary

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.

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

- 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

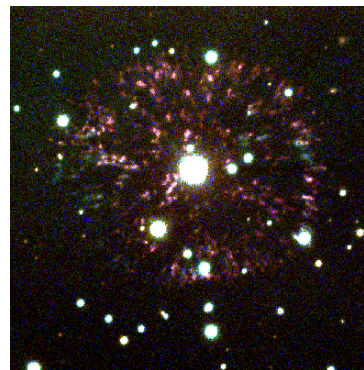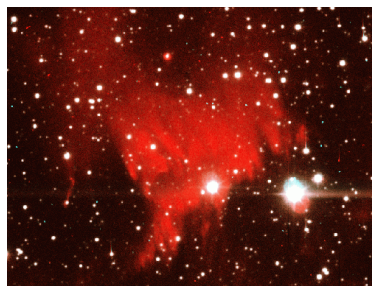Nova Cygni 1975

V1500 Cygni

A "fast" nova
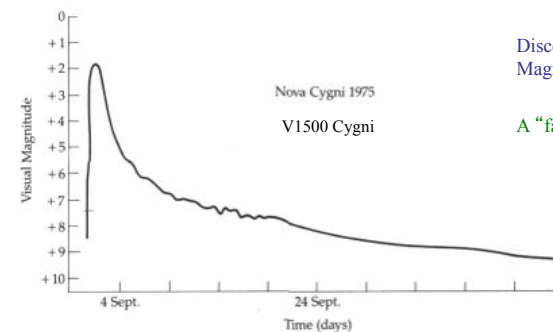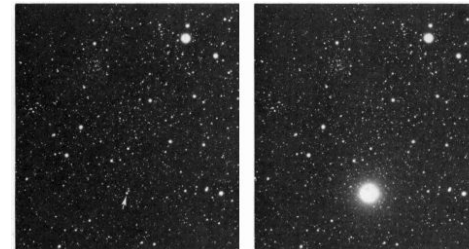
Novae

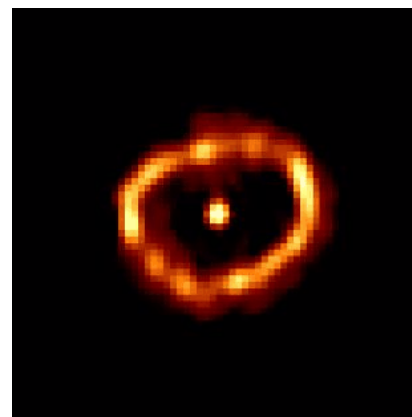- Nova Vel 1998 (3rd magnitude)

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.
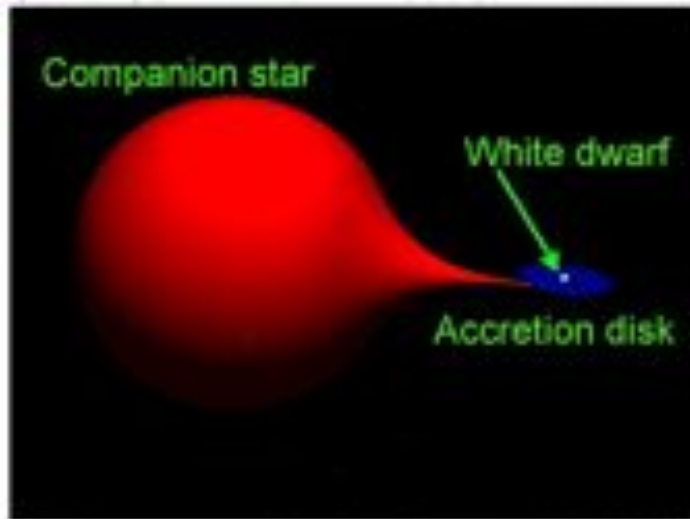
Nova Cygni 1992

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 x 10^{-4} solar masses

Companion star
White dwarf
Accretion disk

The companion star is typically a low mass (K or M) main sequence star. The orbital period is short < 1 day.
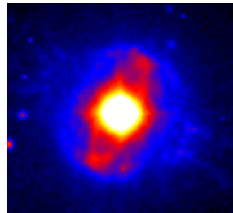
An earth mass or so is ejected at speeds of 100s to 1000s of km s^{-1}. Years later the ejected shells are still visible. The next page shows images from a ground-based optical survey between 1993 and 1995 at the William Hershel Telescope and the Anglo-Australian Telescope.
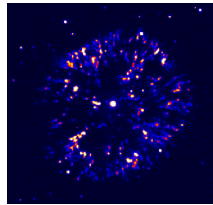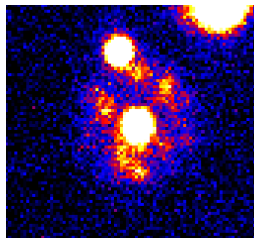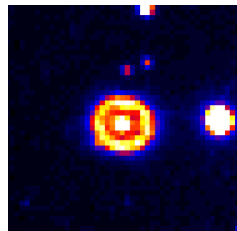

Nova Persei (1901)
GK Per
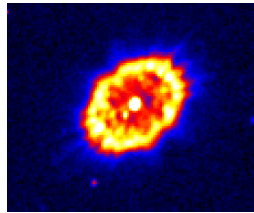
Nova Hercules (1934)
DQ - Her

Nova Pictoris (1927)
RR Pic

Nova Cygni (1975)
V1500 Cygni

Nova Serpentis (1970)
FH Ser

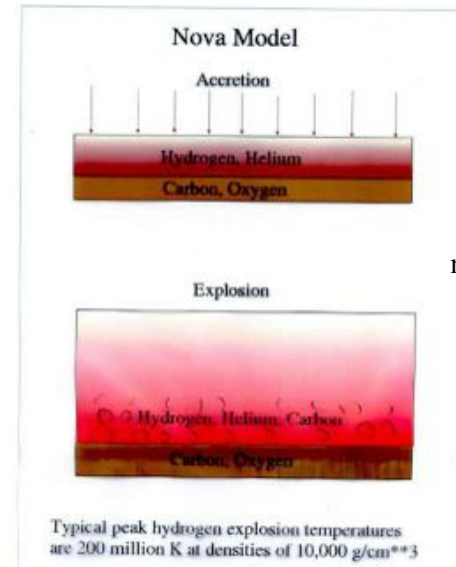http://www.jb.man.ac.uk/~tob/novae/

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

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

$$\frac{GM}{R} = \left(\frac{(6.67 \times 10^{-8})(2 \times 10^{33})}{5 \times 10^8} \right)$$
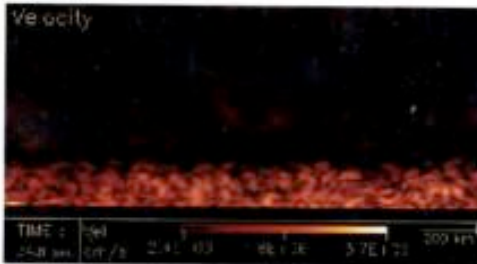
$$\approx 3 \times 10^{17} \text{ erg g}^{-1} \ll 6.8 \times 10^{18} \text{ erg g}^{-1} = q_H$$

- 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.
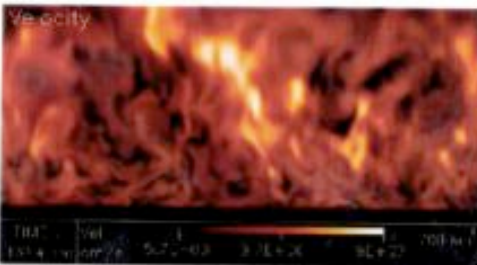
- Accretion then resumes and the cycle repeats

Nova Model

Accretion

Hydrogen, Helium
Carbon, Oxygen

Explosion

Hydrogen, Helium, Carbon
Carbon, Oxygen

Typical peak hydrogen explosion temperatures are 200 million K at densities of 10,000 g/cm**3

nb. Novae can *repeat!*

accrete
explode
accrete
explode
.
.
.

Kercek et al (1999)

About
5000 trillion
megatons/sec

Nucleosynthesis from novae – not much,
 but a couple of isotopes that can't be made elsewhere

   ^{15}N, ^{17}O

The more common isotopes of nitrogen and oxygen – ^{14}N and ^{16}O are made elsewhere in planetary nebulae and supernovae respectively.

Novae also make some radioactive ^{22}Na (half life 2.6 years which has been searched for but not discovered yet.

Generally novae actually decrease slightly with mass as a consequence of repeated outbursts, but at higher accretion rates the burning shell becomes stable and the mass of the white dwarf can actually grow.

Type Ia
Supernovae
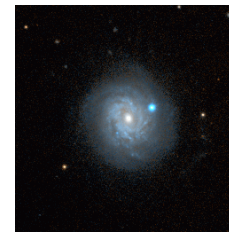
SN 1998aq

SN 1998dh

SN 1998bu

SN 1994D

Type Ia supernovae are the biggest thermonuclear explosions in the universe.

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)

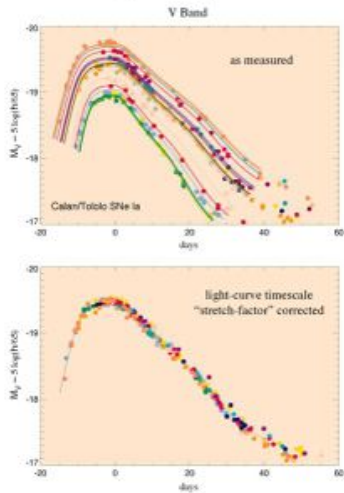- Higher speed, less frequent than Type II

SN 1994D

Spectra are similar from event to event
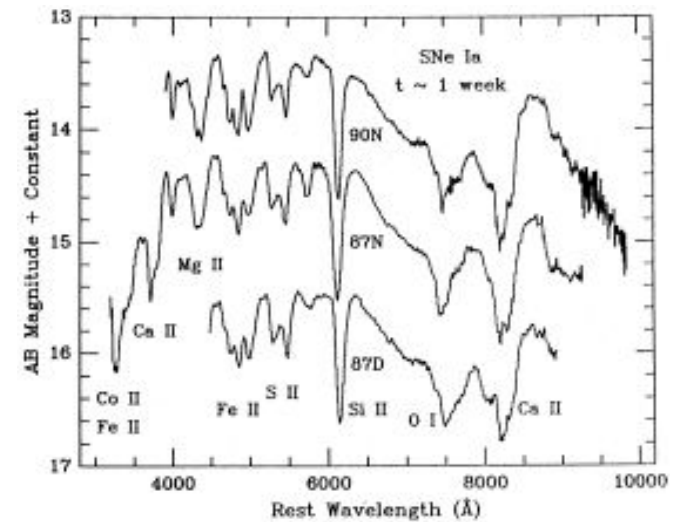
Spectra of three Type Ia supernovae near peak light – courtesy Alex Filippenko

Low Redshift Type Ia Template Lightcurves

The Phillips Relation
(post 1993)

Broader = Brighter

Can be used to compensate for the variation in observed SN Ia light curves to give a "calibrated standard candle".

Note that this makes the supernova luminosity at peak a function of a single parameter – e.g., the width.

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) Leading Model*

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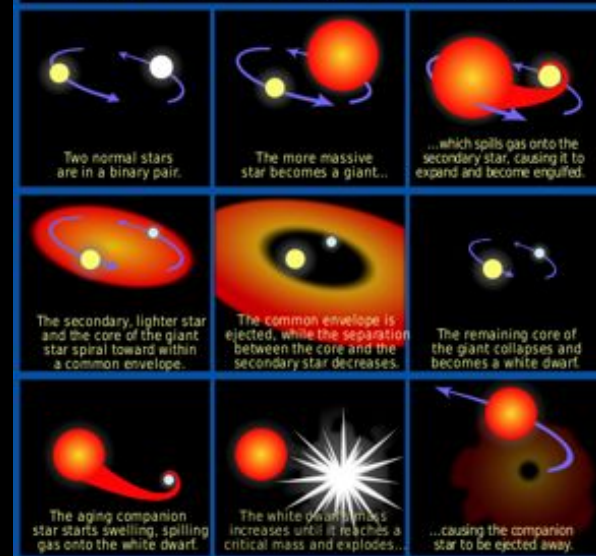

White Dwarf

Mass Transfer
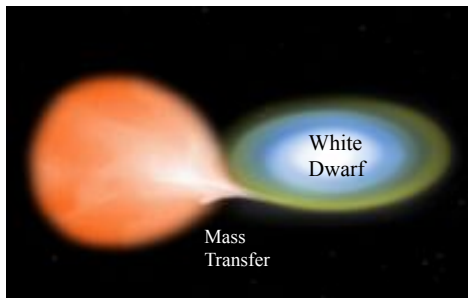
Explains:

• Lack of H in spectrum

• Association with old population

• Regularity

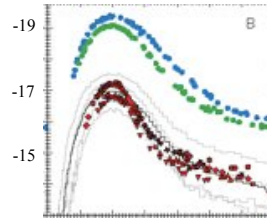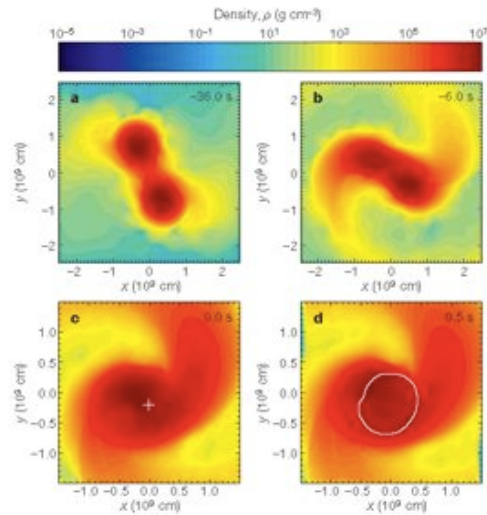• Large production of ^{56}Ni and a light curve dominated by radioactivity.

* well, until recently….
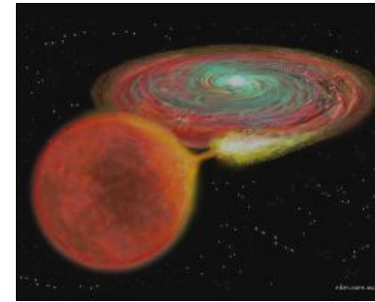
Evolutionary scenario

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
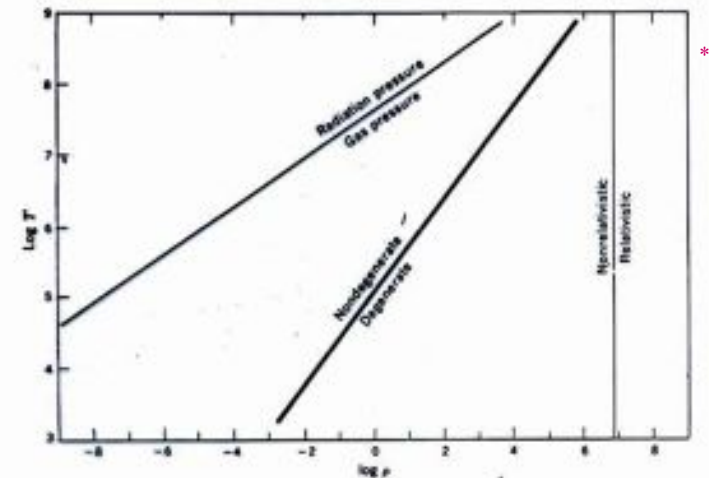must be maintained for millions of years.

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

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.

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

$$M \approx 1.38 M_\odot$$

P is independent of T, but

$\varepsilon_{nuc} \propto T^{26}$ for carbon burning

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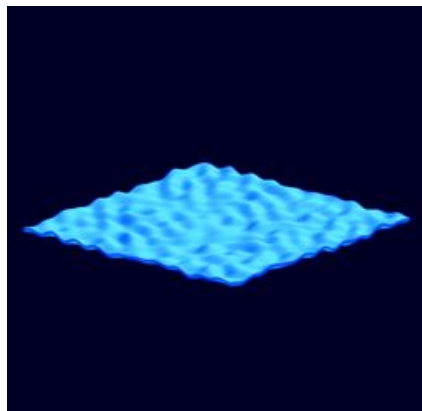
Ignition at $\rho_c \sim 3 \times 10^9$ because:

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.
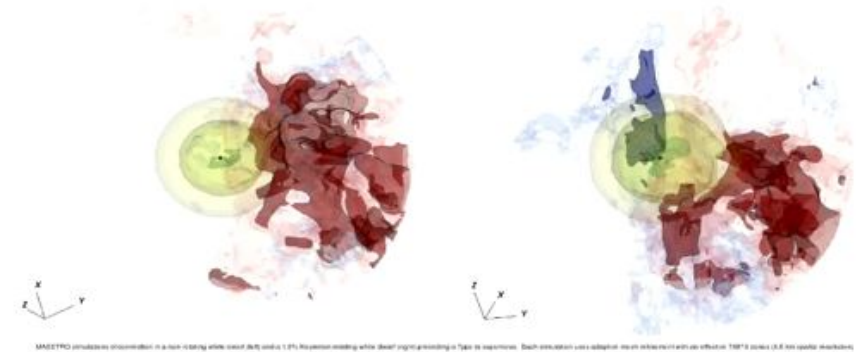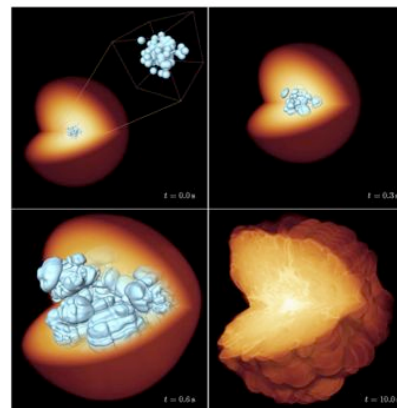

Explosion preceded by about a century of convection. The convection is asymmetric
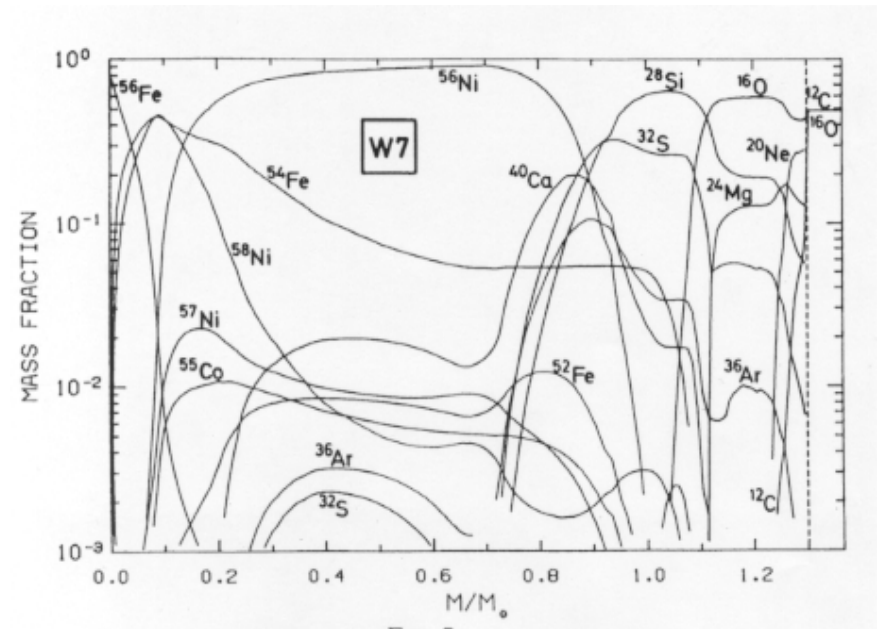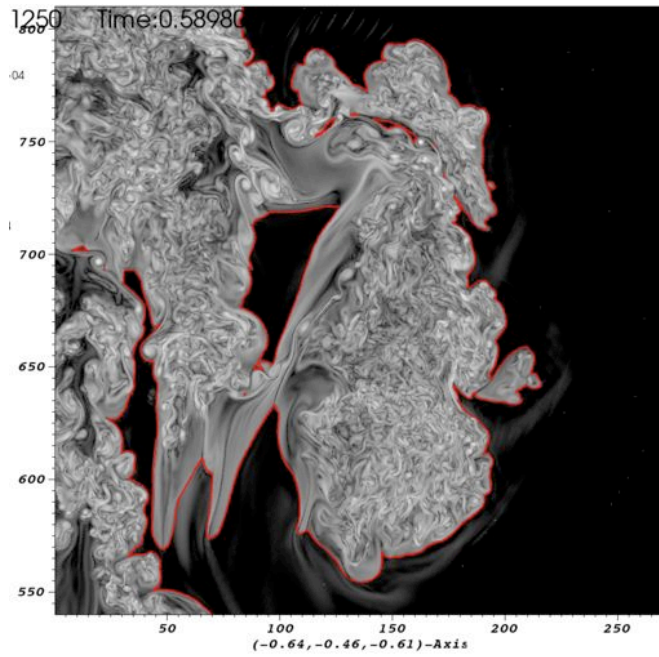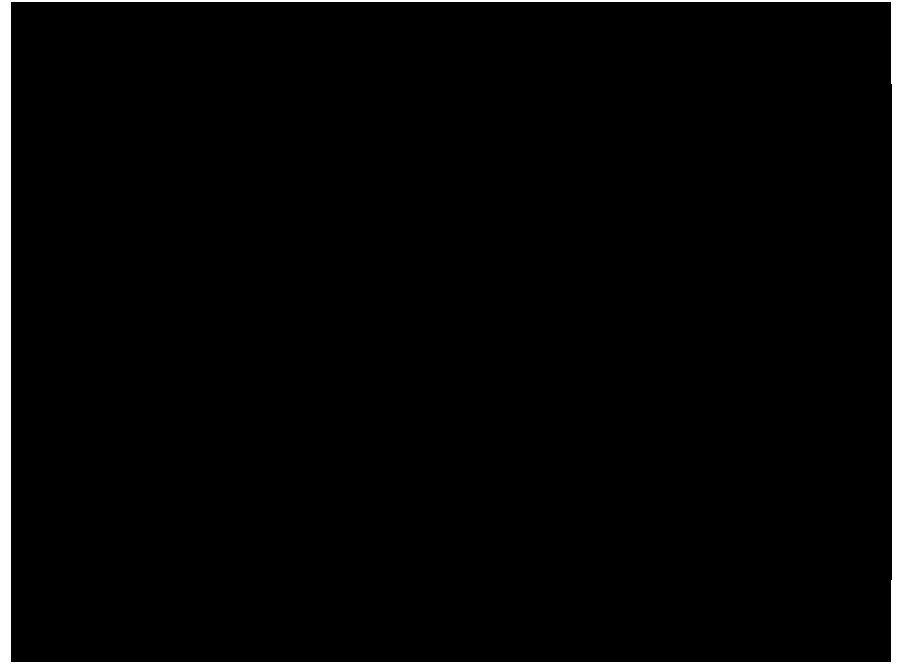
The Explosion - Burning and Propagation

Zingale et al. (2005)　　　　Roepke and Hillebrandt (2007)

1250   Time:0.58980

(-0.64,-0.46,-0.61)-Axis

W7

0.7 $M_\odot$ of ^{56}Ni

0.94 $M_\odot$ of ^{56}Ni

SN Ia probably make about 2/3– 3/4 of the iron
group elements found in nature
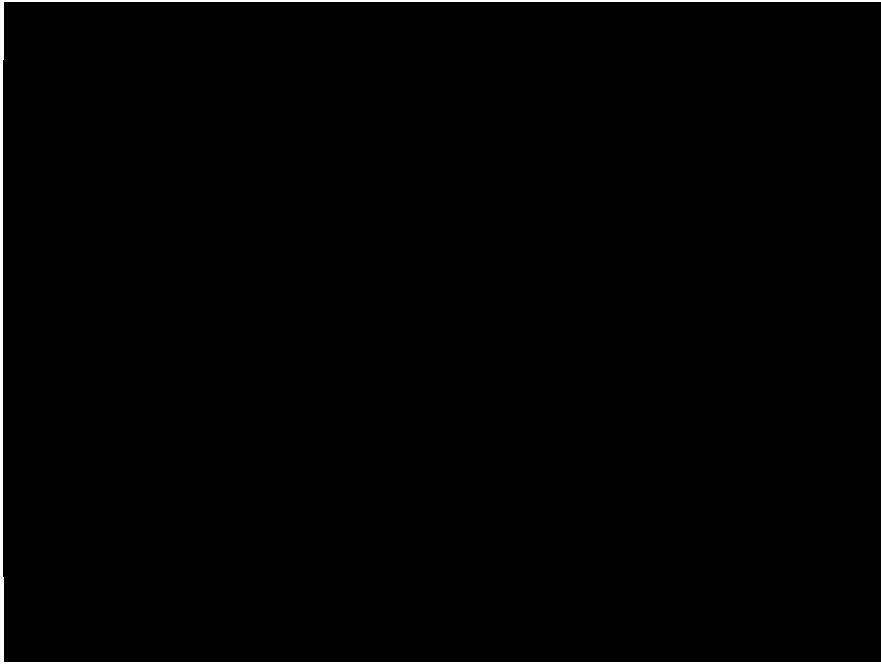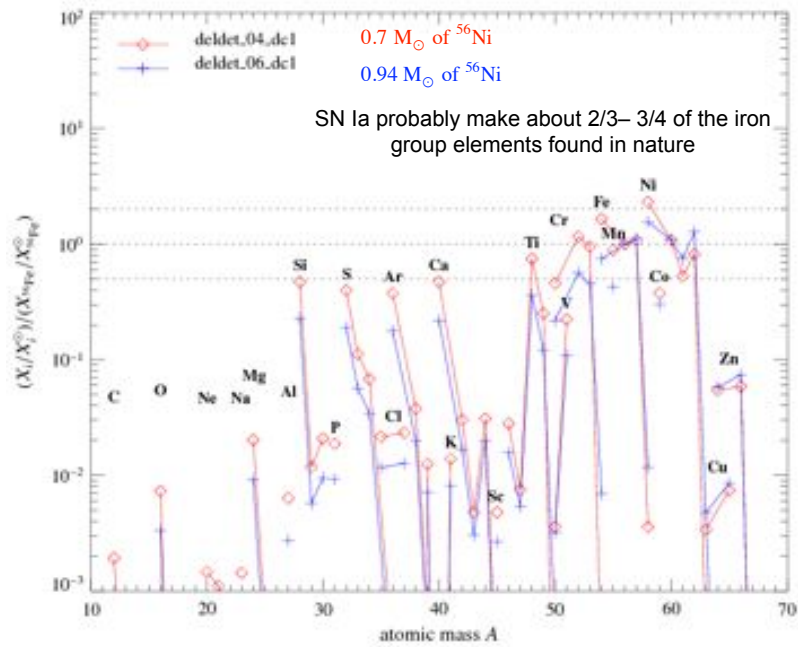
Qualitative Type Ia Supernova Light Curve

^{56}Ni + ^{56}Co decay

Entirely due to radioactivity

Diffusion and expansion time
scales approximately equal

Optical light curve

gamma-ray
escape

Radioactivity

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

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

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

$$q = 6.4 \times 10^{16} \, erg/gm$$
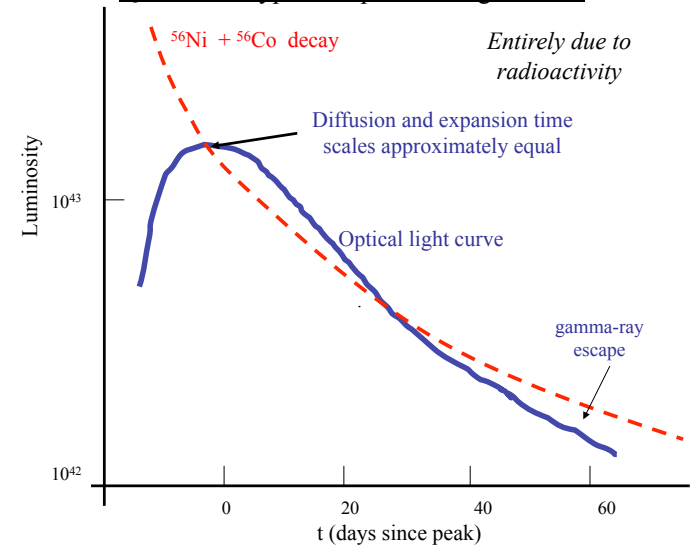
0.6 solar masses of radioactive Ni and Co can thus provide
1.1×10^{50} erg at late times after adiabatic expansion is
essentially over.

strong deflagration
weak detonation

weak deflagration
strong detonation

t = 6.0 days
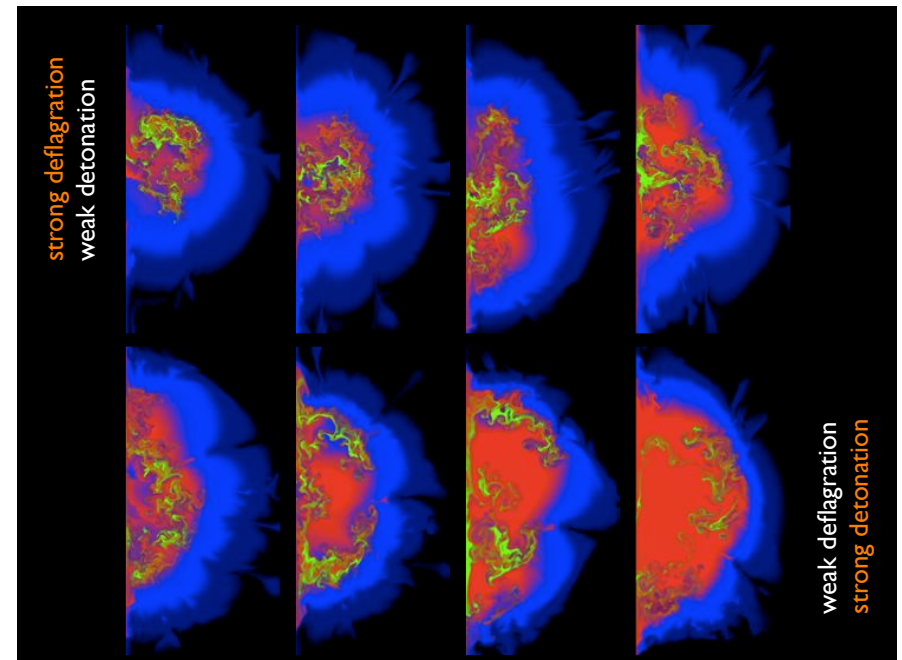
SN 2003 du
vs
Model

Supernova
(Death of a star)

Type Ia

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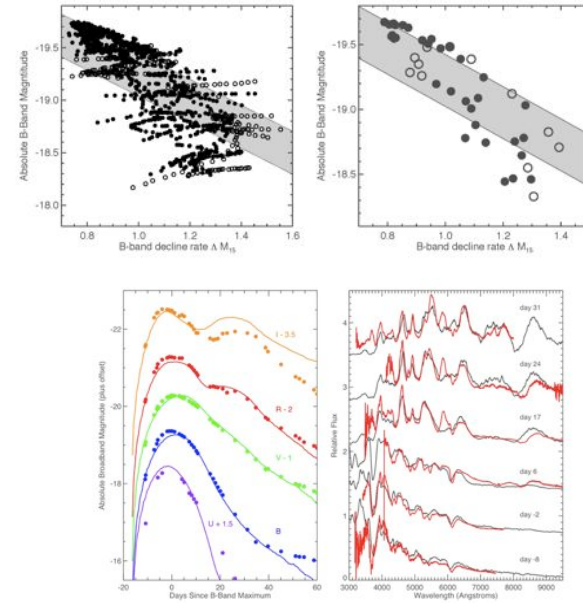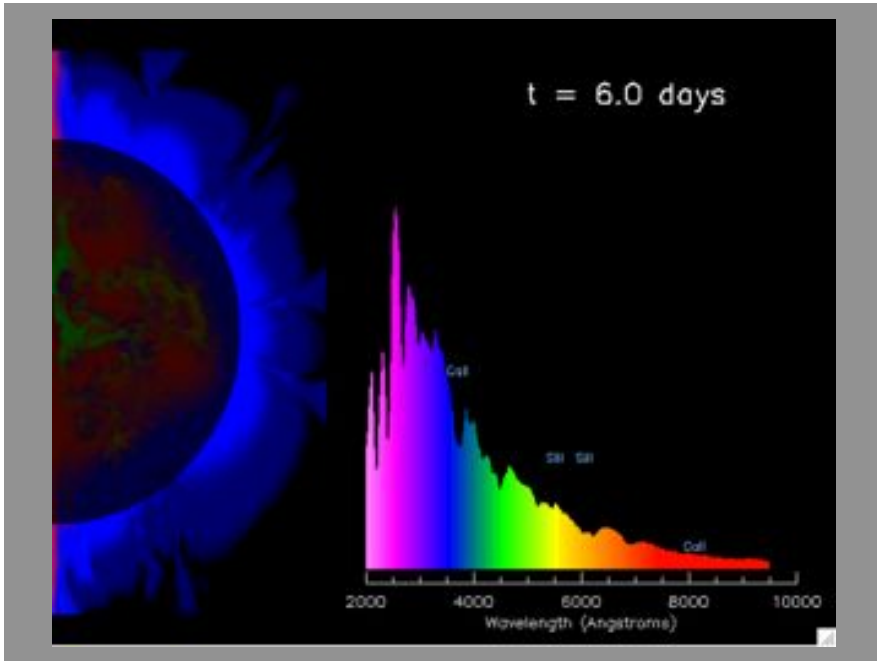- 1/200 yr in our Galaxy
- Makes about 2/3 of the iron in the Galaxy

Type II

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

The bright x-ray sky – mostly point sources
(AGN, SNR, black holes and neutron stars)
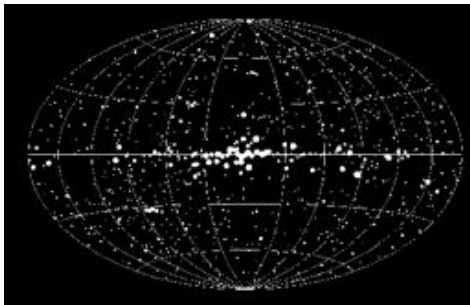
HEAO survey completed 1978
841 sources mostly binary systems
containing a neutron star or a black hole.

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

Active Galaxies   Binary Star Systems
Black Holes   Cataclysmic Variables
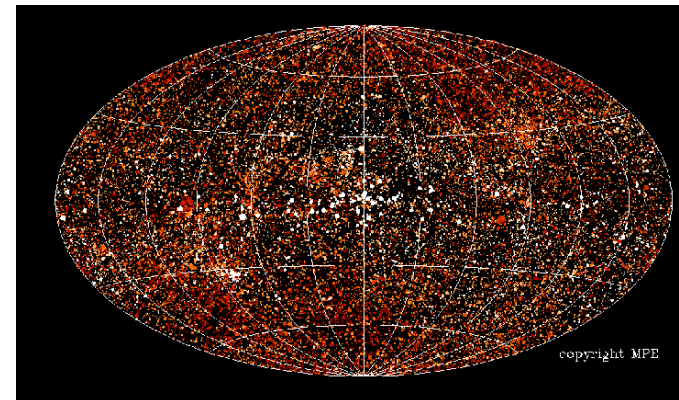Dark Matter??   Diffuse Background
Gamma-ray Bursts   Neutron Stars
Pulsars   Stars
The Sun   Supernovae and their Remnants
White Dwarfs   X-ray Transients

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.

• 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.

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})

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

$$L = \frac{GM\dot{M}}{R}$$
$$= \frac{(6.67 \times 10^{-8})(1.4)(2 \times 10^{33})(6 \times 10^{17})}{1.0 \times 10^{6}}$$
$$= 1 \times 10^{38} \text{ ergs}^{-1}$$

- This is still approximately blackbody radiation, so

$$T_{eff} \approx \left(\frac{L}{4\pi R^2 \sigma}\right)^{1/4}$$
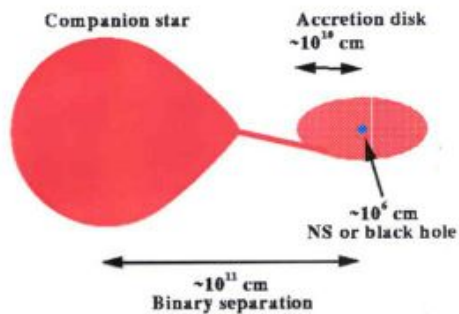$$= 2 \times 10^7 \text{ K}$$

$R \approx 10$ Km

which corresponds to x-rays

$$\lambda_{max} = \frac{0.289 \text{ cm}}{T_{eff}} = \frac{2.89 \times 10^7 \text{ Angstroms}}{T_{eff}}$$
$$\approx 3 \text{ Angstroms (X-rays)}$$

Accreting neutron star or black hole

Companion star

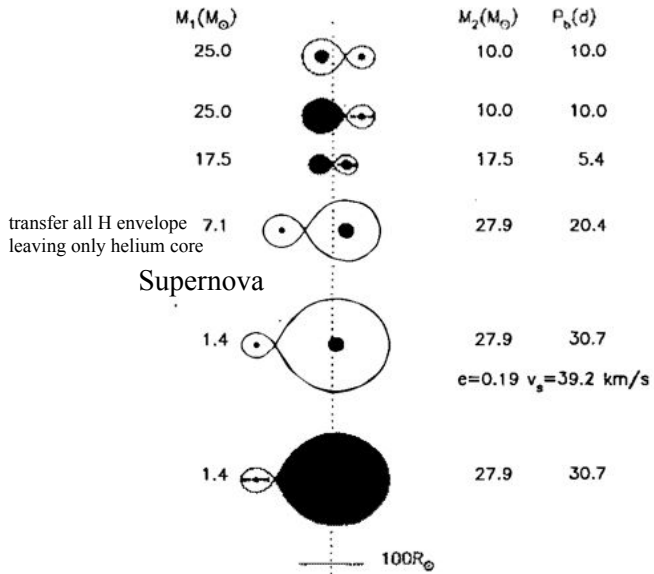Accretion disk ~10^{10} cm

~10^6 cm NS or black hole

~10^{11} cm Binary separation

Luminosity ~10^{36}–10^{38} erg s^{-1} = 200–50,000 L$_\odot$

Temperature of disk ~10^7 K $\Rightarrow$ primarily X-rays

Black Hole Illustration
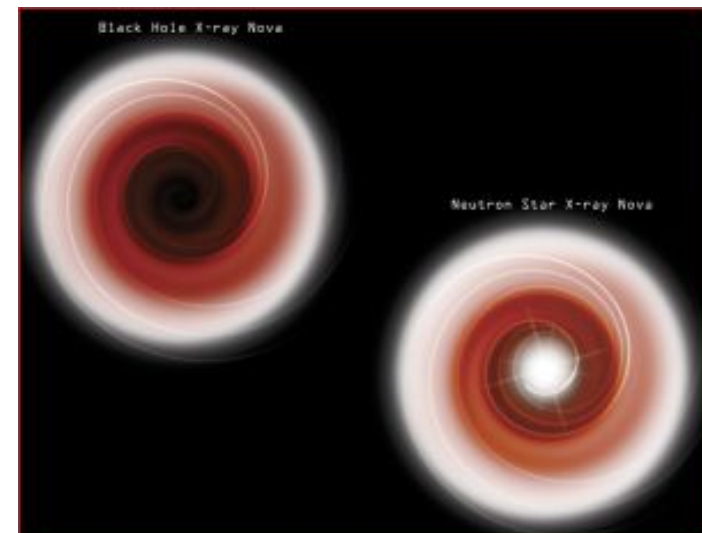
High Mass X-Ray Binary Formation

$M_1(M_\odot)$		$M_2(M_\odot)$	$P_b(d)$
25.0		10.0	10.0
25.0		10.0	10.0
17.5		17.5	5.4
transfer all H envelope leaving only helium core 7.1		27.9	20.4

Supernova

1.4		27.9	30.7
	$e=0.19\ v_s=39.2$ km/s		
1.4		27.9	30.7

$100R_\odot$

Cyg X-1 in X-Rays

exosat Observatory
cma1 detector
Exposure time : 4351 seconds
Field name : CYGNUS X-1
21 arcsec
N E
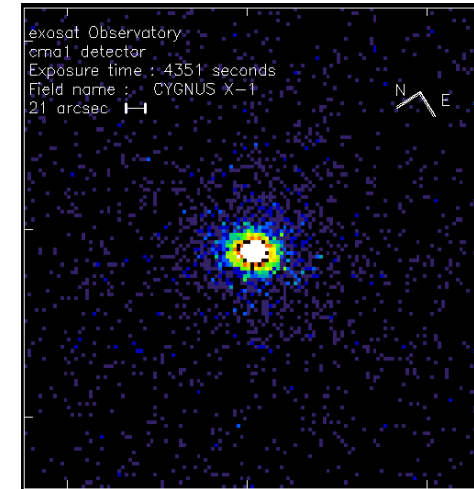
Artist's Rendition of Cyg X-1

Black hole candidates

Source	Companion	P (days)	Mass
Cygnus X-1	B supergiant	5.6	6-15
LMC X-3B	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
+ 2 more			

Fraknoi, Morrison, and Wolff p. 328