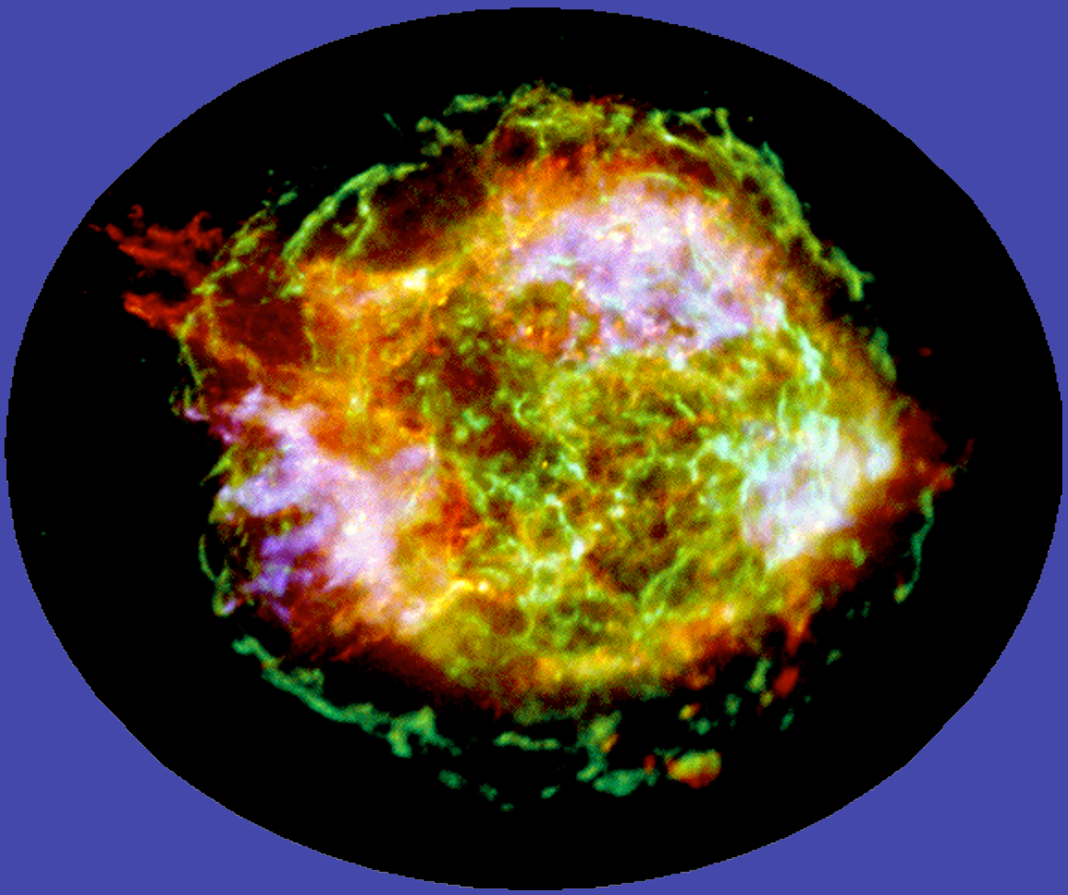
In The News ...



1 Msec Chandra ACIS-S observation of the Cas A supernova Remnant. This is the deepest X-ray image of a supernova remnant ever obtained.
It supports the idea that SN are significantly (importantly) non-spherical.

RECAP: Nuclear Evolution

Star with M>8Msun can achieve core temperatures which are high enough to fuse C (about 6×10^8 K)

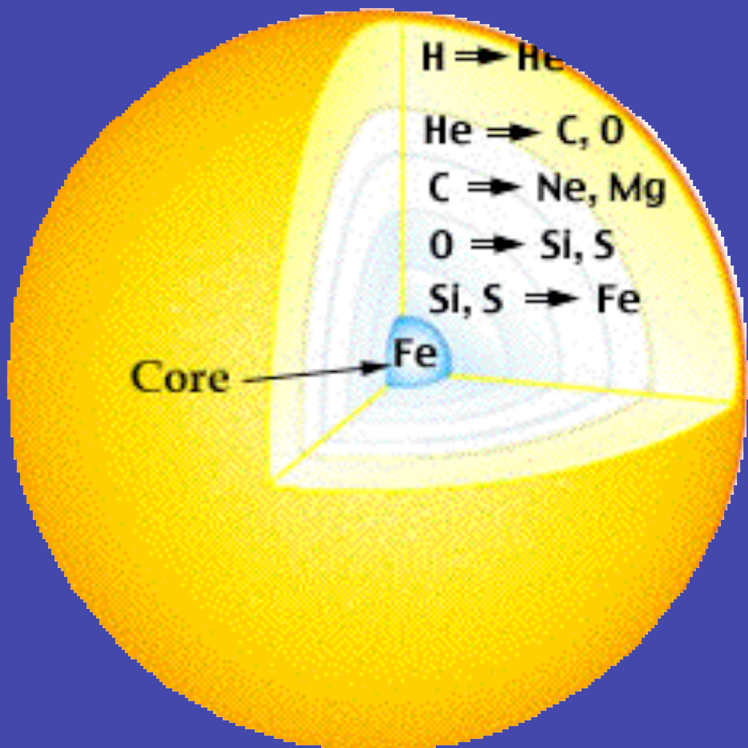
Nuclear burning stages: Log(duration/yr) for a 75 M_O star

Mass	H	He	C	Ne	O	Si
75M_O	6.5	5.7	3.0	-0.2	-0.1	-2.2

From Woosley & Heger 2002

2 days!

Nucleosynthesis past C



nuclear burning in shells gradually results in formation of heavier nuclei (Ne, Mg, O, Si, S)

After Si burns to Fe, stellar core no longer has a means of pressure support: fusion or fission of Fe robs core of energy

Core collapse

End States

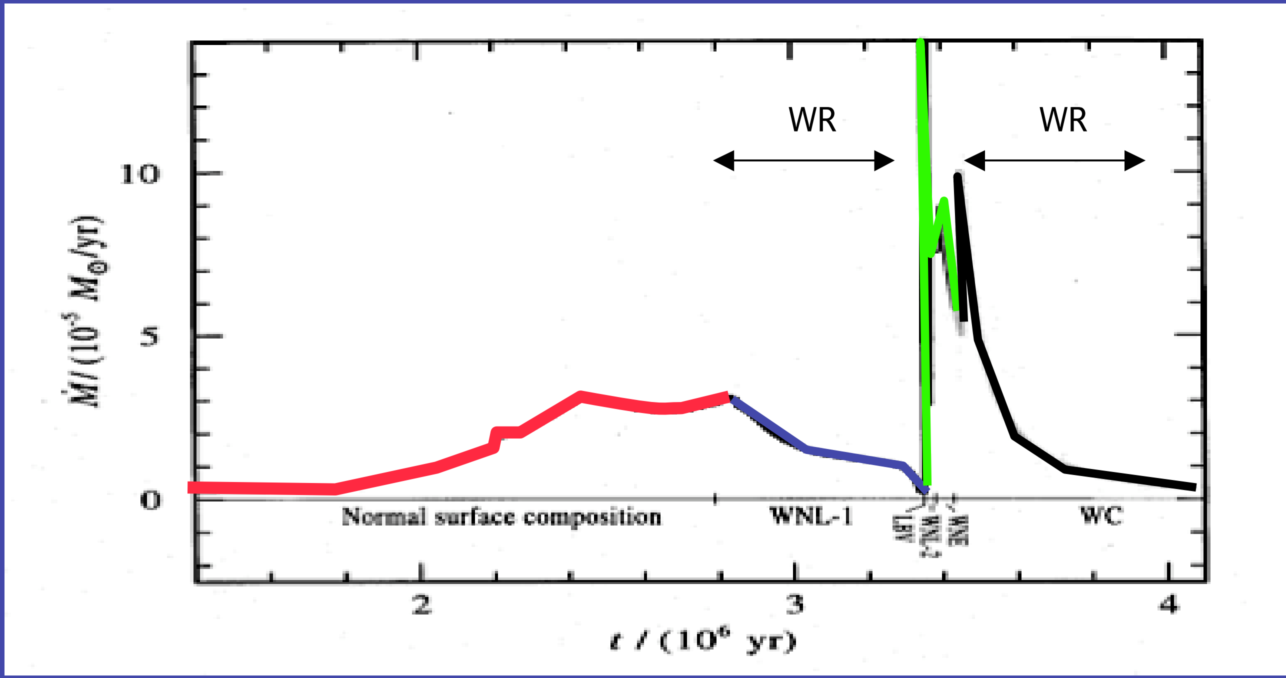
Subsequent evolution after the formation of the Fe core extremely rapid (seconds)

Outer envelope ejected as a supernova explosion (supernova remnant)

core either:

- is completely destroyed
- becomes a neutron star
- or becomes a black hole

Surface Evolution



From Langer et al. 1994

	M	log(t/yr)	M_{lost}	M_{end}
MS	60.0	6.5	17.6	42.4
WN	42.4	5.8	21.7	20.7
LBV	20.7	4.9	5.4	15.3
WNE/WC	15.3	5.8	11.4	3.9

The surface of the star evolves as well. As the atmosphere becomes contaminated with heavier elements (N, C, O) radiative driving becomes more efficient. Star can lose most of it's mass via its stellar wind.

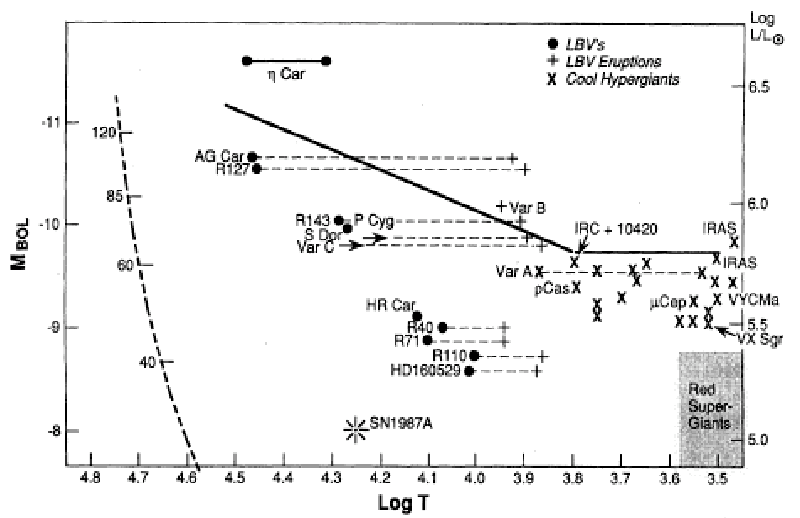
Wolf-Rayet Stars

Very massive stars will evolve to “Wolf-Rayet” stars, characterized by strong emission lines produced by an optically thick stellar wind.

During this phase the mass loss rate increases by about a factor of 10.

Only a few hundred WR stars are known

Luminous Blue Variables



Humphrey and Davidson 1994

Humphreys-Davidson limit: In the upper HRD, there's a boundary beyond which stars don't exist in a stable configuration.
Stars near this limit are also near the Eddington Limit (where radiation pressure on electrons exceeds gravity)
Stars near this limit are sometimes called Luminous Blue Variables

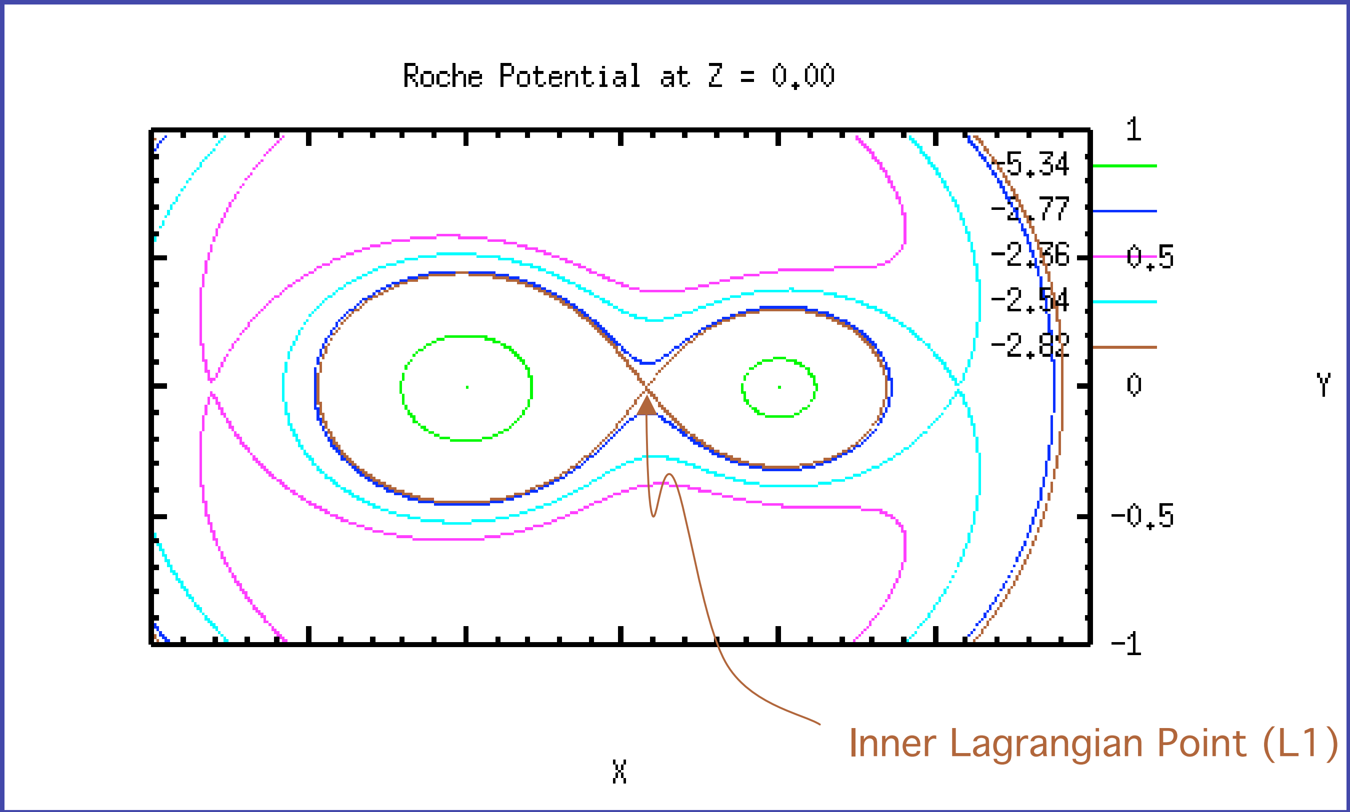
$$L_E = 4\pi G M m_p c / \sigma_T = 1.2 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ ergs s}^{-1}$$

Binary Star Evolution

Stars in binary systems evolve individually and together

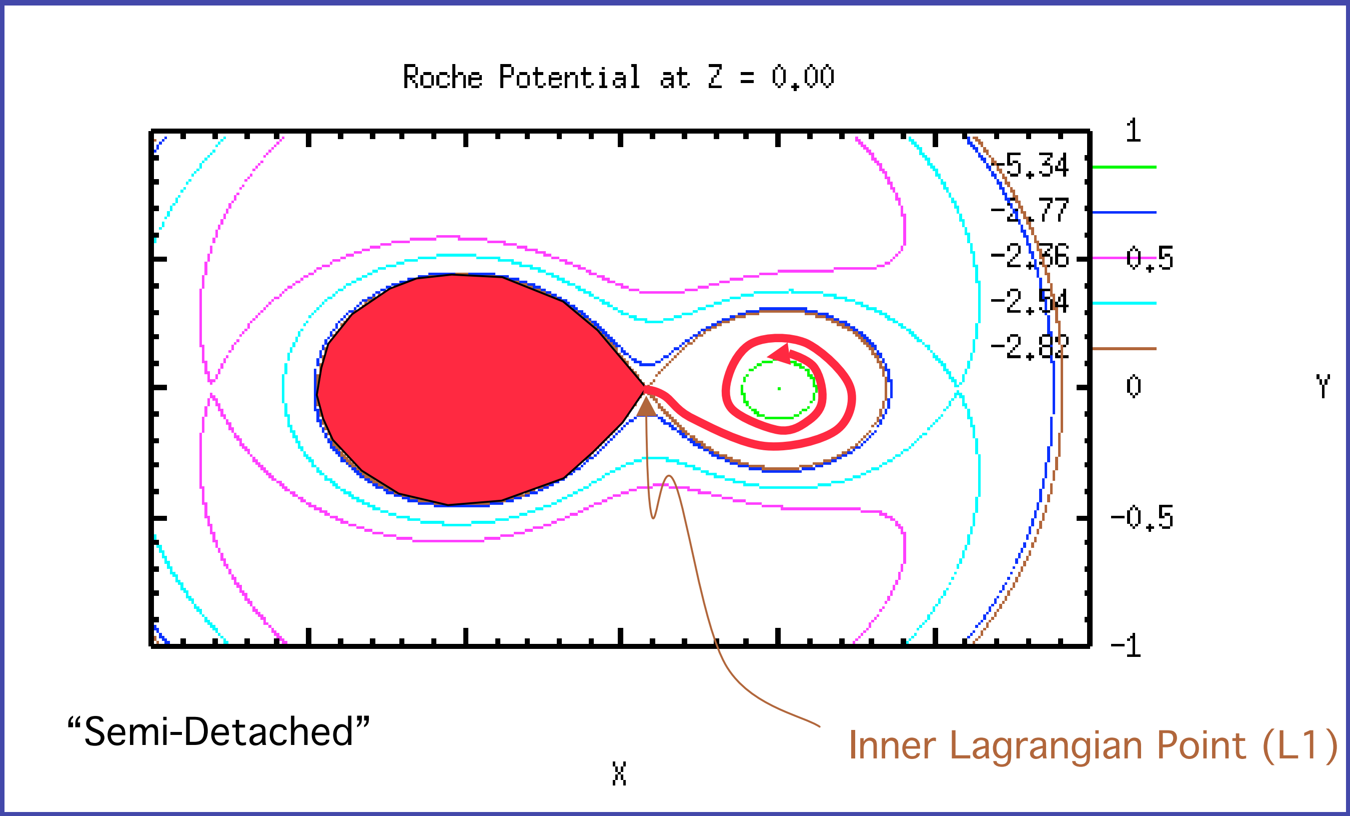
- individually: evolution follows normal progression based on mass
- together: stars can interact, exchange mass, angular momentum...

Equipotentials



Along the equipotential, the gravitational + centrifugal potentials = constant

Evolution along an Equipotential



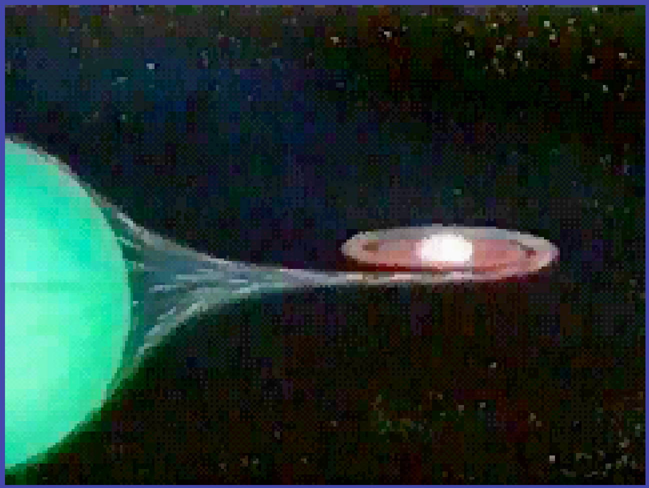
As more massive star moves towards the Red Giant Phase, it encounters the critical Roche equipotential and mass is transferred from the primary to the secondary through the ILP

Interactions

Mass transfer can either be

- conservative: mass lost by primary is gained by the secondary
- non-conservative: mass lost by the primary is lost to the system
- or some combination

Stars in binaries can exchange angular momentum
Also interact tidally



Algols

Mass ratios are a function of time.

Mass exchange can make the star which originally had the lower mass more massive than the (originally) higher mass star

Algol Paradox: Algol (β Per), B8 dwarf + K giant; giant star more evolved but less massive: how?

⇒ due to mass transfer from the originally more massive star to its companion:

Summary

Star formation driven by gravity vs. kinetic energy, spin, magnetic field: disks and jets important

Angular momentum can be stored in a stellar companion, or in a stellar disk

Evolution of a star driven by mass

Low mass and high mass stars evolve differently

Single and binary stars evolve differently

Eventually stars die

Cosmic Explosions

The death of stars is usually associated with a tremendous release of gravitational and/or nuclear energy

Stellar explosions inject a large amount of energy into the ISM

Explosions also produce and distribute new atoms

Explosions come in 2 types:

- Star destroyed: Supernova
- Star not destroyed: Nova

SN Characteristics

Supernovae: sudden, very extreme brightening of a star (by ~1-10 billion times)

No recurrence

Occur about once every 50 years or so on average

The Milky Way is overdue for a SN

Novae: sudden brightening (~10-10^6 times); can recur

Historical Supernovae

Year	Report	Status
185 A.D.	Chinese	id in doubt (Chin and Huang 1994)
386	Chinese	unknown
393	Chinese	unknown
1006	China, Japan, Korea, Arab lands, Europe	Identified with radio SNR
1054	China, Japan	Crab Nebula
1181	China, Japan	radio SNR 3C58?
1572	Europe (Tycho Brahe), China, Japan	Tycho's remnant
1604	Europe (Kepler), China, Japan, Korea	Kepler's remnant

see http://astrosun2.astro.cornell.edu/academics/courses/astro201/sn_history.htm

SN 1006 brightest in recorded history:

The annals of the Benedictine monastery of St Gallen in Switzerland record the following entry for the year 1006. "A new star of unusual size appeared, glittering in aspect, and dazzling the eyes, causing alarm .... It was seen likewise for three months in the inmost limits of the South, beyond all the constellations which are seen in the sky" (Pannekoek 1961).

Supernovae Types

Supernovae are divided into two types (Type I and II, Minkowski 1940) based on the characteristics of their lightcurves and their optical spectra.

SUSPECT: on-line library of observed SN lightcurves and spectra

http://bruford.nhn.ou.edu/~suspect/

Lightcurve Morphologies

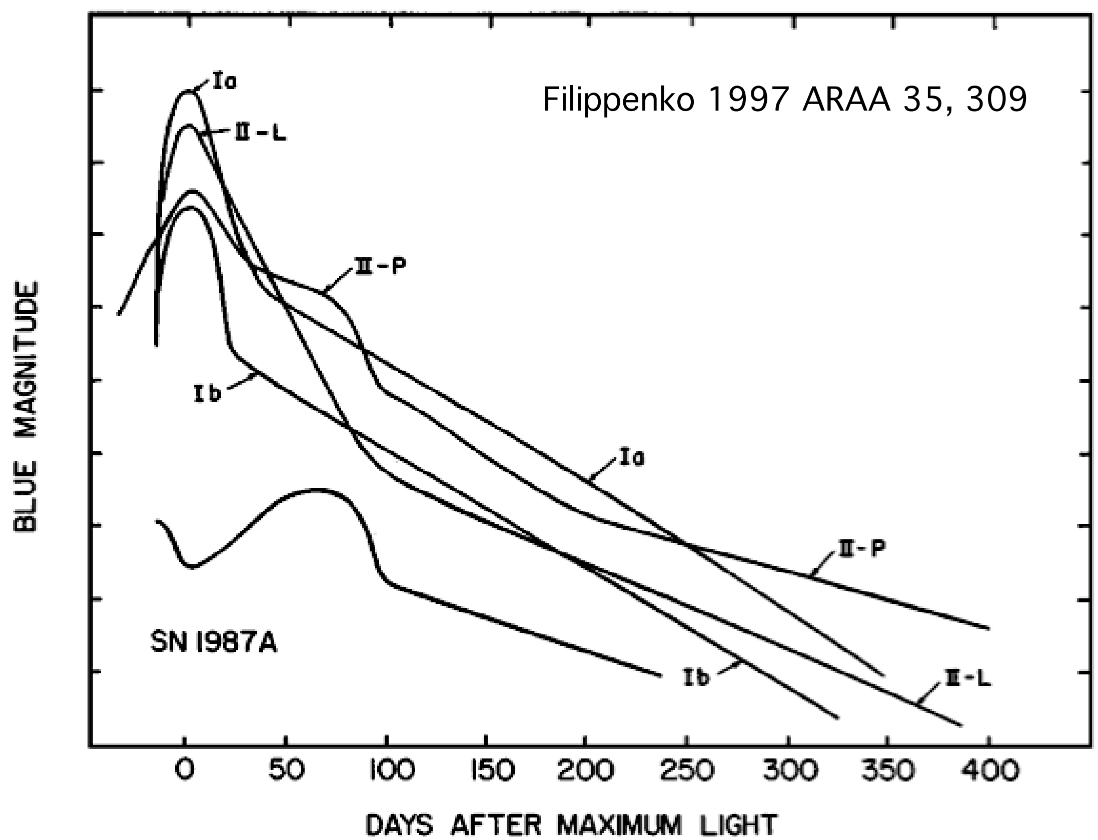


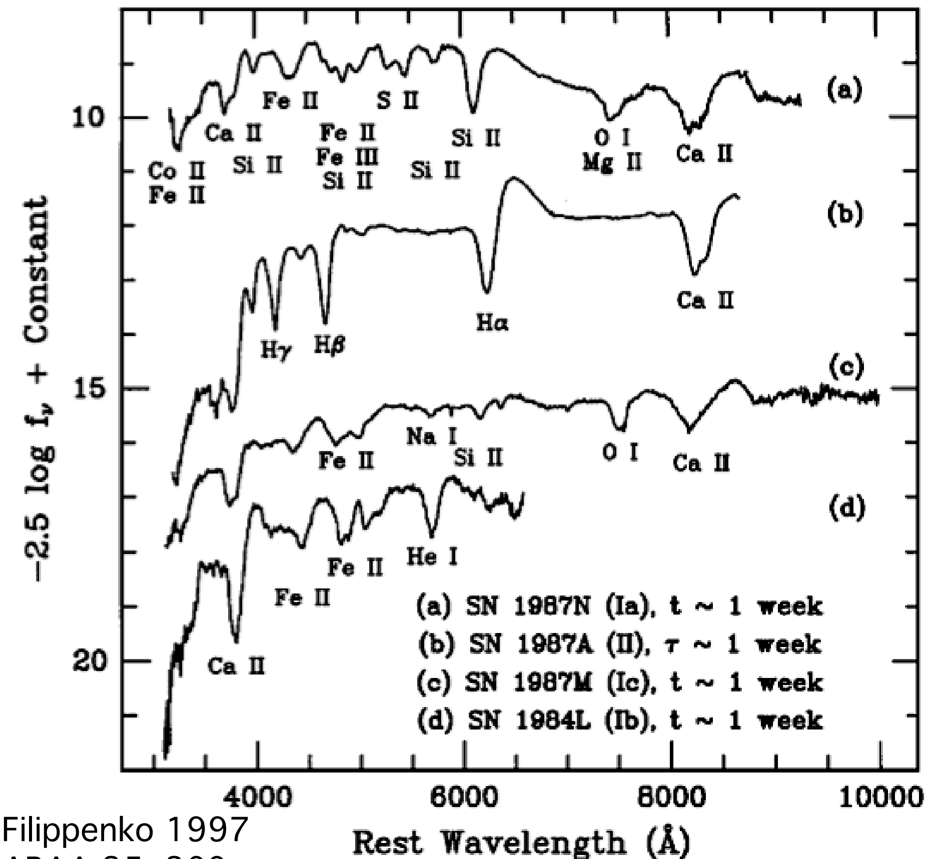
Figure 3 Schematic light curves for SNe of Types Ia, Ib, II-L, II-P, and SN 1987A. The curve for SNe Ib includes SNe Ic as well, and represents an average. For SNe II-L, SNe 1979C and 1980K are used, but these might be unusually luminous. From Wheeler 1990; reproduced with permission.

Type I: all show similar lightcurves (similar precursors?) - rapid rise, short maximum, ~exponential decay

Type II: more varied; less luminous than Type I, longer rise, slower decay

Note: hard to catch SN prior to maximum light

Spectral Morphologies- Around Maximum Light



Filippenko 1997
ARAA 35, 309

Figure 1 Spectra of SNe, showing early-time distinctions between the four major types and subtypes. The parent galaxies and their redshifts (kilometers per second) are as follows: SN 1987N (NGC 7606; 2171), SN 1987A (LMC; 291), SN 1987M (NGC 2715; 1339), and SN 1984L (NGC 991; 1532). In this review, the variables *t* and *τ* represent time after observed B-band maximum and time after core collapse, respectively. The ordinate units are essentially "AB magnitudes" as defined by Oke & Gunn (1983).

Type I vs Type II: Type I shows no H lines; Type II shows strong H lines

Type I: progenitors are stars which have lost most of their H envelopes (WDs [Ia], WRs [Ibc])

Type II: progenitors still have most of their H envelope (RSGs, BSGs)

SNR Evolution

After explosion, what happens?

Stellar matter (envelope) ejected by the explosion moves outward into space and forms a “Supernova Remnant” (SNR), which evolves with time

Three stages of SNR expansion:

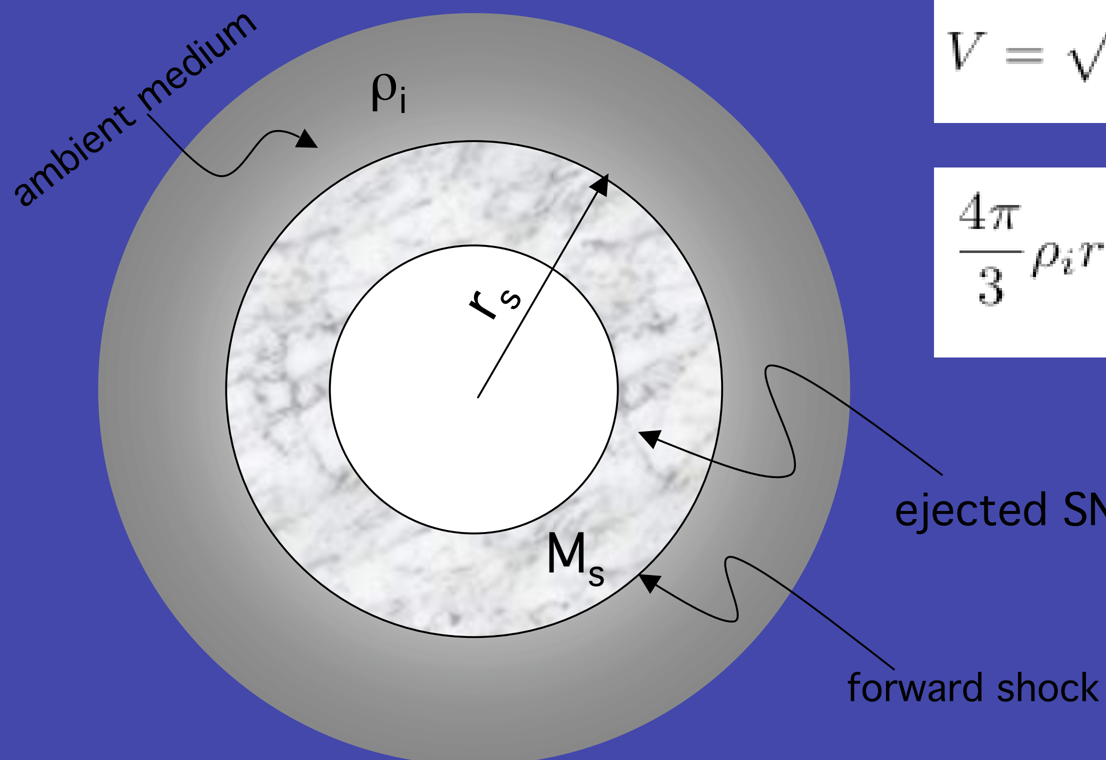
1. Free expansion
2. Non-radiative deceleration
3. Radiative (Isothermal) Expansion

1. Free Expansion

Initially the expansion of the SNR into the ISM is unimpeded, since the density of the ISM is so low (especially if a stellar wind has already cleared out the immediate surroundings)

During this stage, velocity of the remnant is nearly constant with time

This phase lasts until the mass of the swept-up ISM material is about equal to the initial mass expelled by the SN:



$$V = \sqrt{2E/M_s}$$

typically
$E \sim > 10^{47-52}$ ergs
$M_s \sim 1\text{-}4 M_\odot$
$V \sim 5000\text{-}20000$ km/s

$$\frac{4\pi}{3}\rho_i r_s^3 = M_s$$

initial expelled mass

2. Non-radiative deceleration

Swept up mass exceeds mass ejected in the SN

Shell temperature sufficiently high ($T \sim 10^7$ K) so radiation not important

Total Energy of shell = initial energy of shell

$$T_2 = \frac{3\mu}{16k} V_s^2 = \frac{0.061\mu}{k} \frac{E}{\rho_1 r_s^3}$$

$$r_s = \frac{0.26 (t \text{ years})^{2/5}}{n_H^{1/5} \text{ parsecs}}$$

$$T_2 = \frac{1.5 \times 10^{11}}{(t \text{ years})^{6/5} n_H^{2/5}} \text{ K}$$

"Sedov Phase" or adiabatic phase

3. Radiative (Isothermal) Expansion

After the SNR shell temperature drops below ~10^6K (i.e. about $t \sim 10^4$ years after the explosion), abundant ions like C, N, & O begin to recombine, which radiates away the thermal energy and cools the shell.

Expansion driven not by internal pressure but by momentum of the shell: "Snowplow" phase

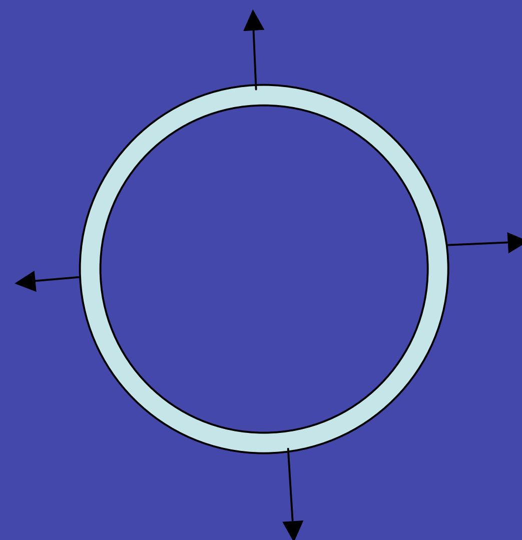
$$M_s v_s = M_t v_t$$

mass & velocity at start of snowplow stage)

$$M \approx \frac{4\pi}{3} \rho_1 r_s^3$$

$$r_s = \frac{3 M_t v_t}{\pi \rho_1} t$$

$$v_s = \frac{3 M_t}{4\pi \rho_1 r_s^3} v_t$$



Material that has crossed the shock is slowed, so that a compressed thin shell forms just behind the shock.

Effects of SN

- Re-shape ISM
- compress IS clouds & aid star formation
- evacuate large regions of the ISM
- produce and distribute heavy elements

Chemical Pollution

Elements through Fe are formed inside the star. When the star explodes, these get distributed to the ISM:
He, C, O, N, Mg, Ne, Si, S...

During the explosion new elements can be formed by rapid production and capture of free neutrons

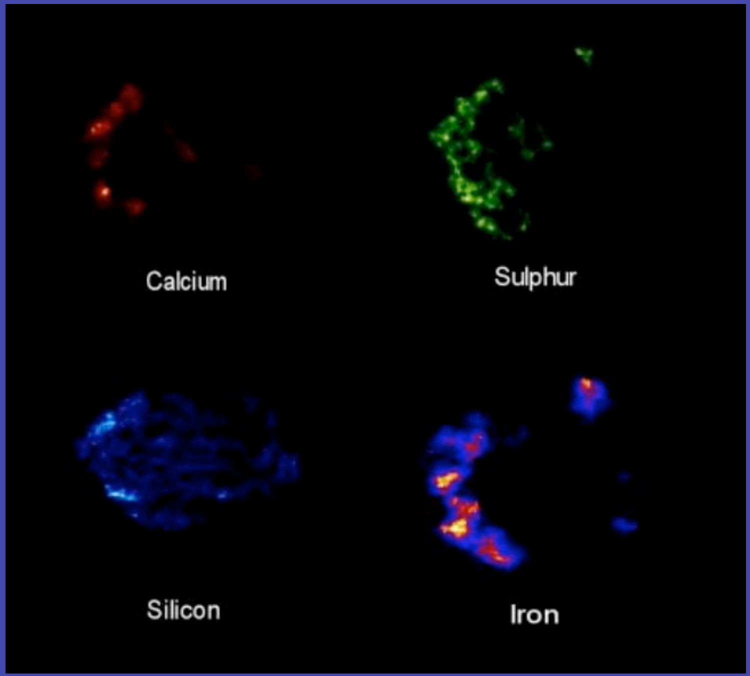
Can build up very heavy nuclei by this “rapid” process (the “r-process”)

see
http://ultraman.ssl.berkeley.edu/nucleosynthesis.html
http://ultraman.ssl.berkeley.edu/anders.txt

Chemical Segregation

Products of nuclear burning don't get distributed uniformly within the ejecta:

- X-ray observations of Cas A suggests that heavier elements (Si for eg) are located in the outer part of the remnant.
- X-ray observations of Tycho's SNR show clear segregation of nuclear burning products:



Credit:

XMM, Dr. B. Aschenbach & ESA; D. Lumb

SN 1987a - Test case

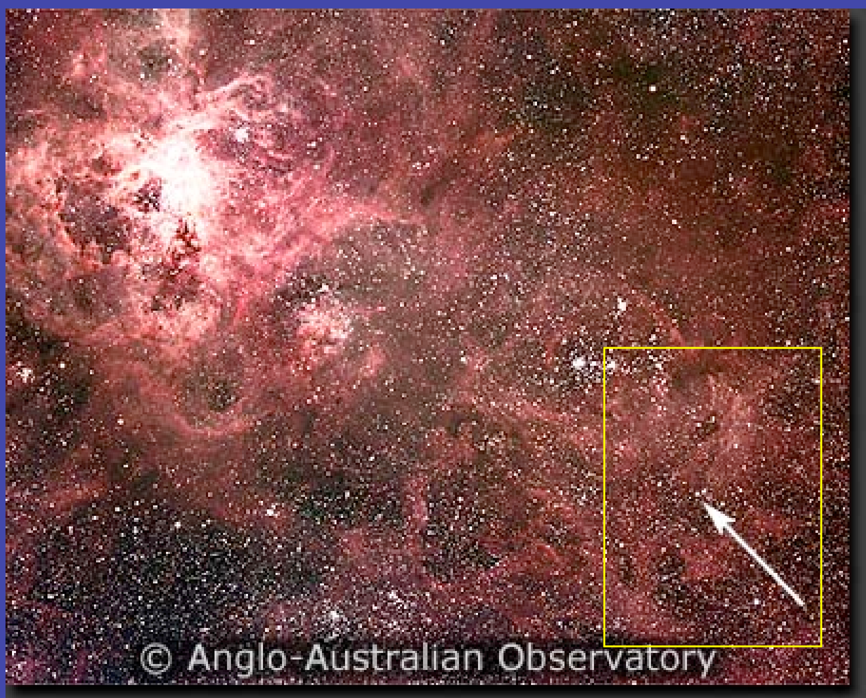
On Feb 23, 1987, light from a new supernova in the LMC reached earth. (The distance to the LMC is about 156,000 ly)

The discovery was made optically by Ian Shelton of the University of Toronto from Las Campanas Observatory, Chile.

SN1987A (as it was named) became the first visible SN in about 400 years. It got as bright as m=2.7

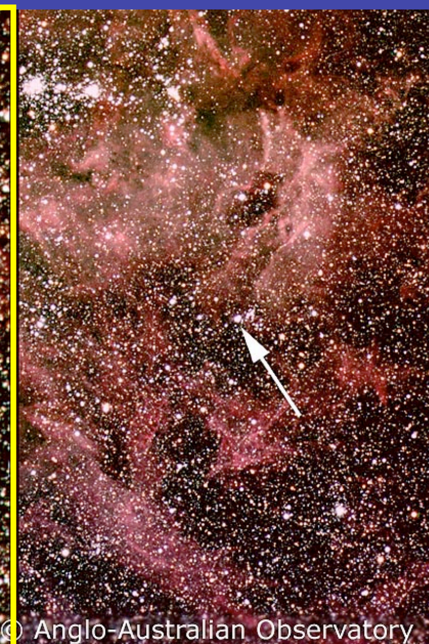
Allowed for modern tests of stellar evolution and SN theories.

SN 1987a - before, during and after



Before

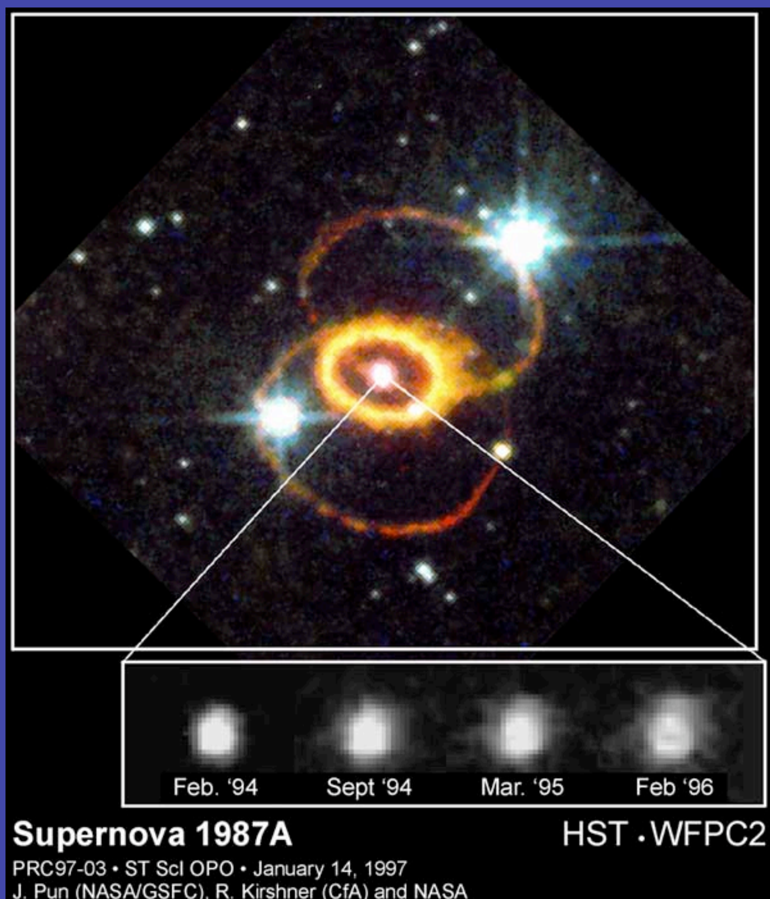
During



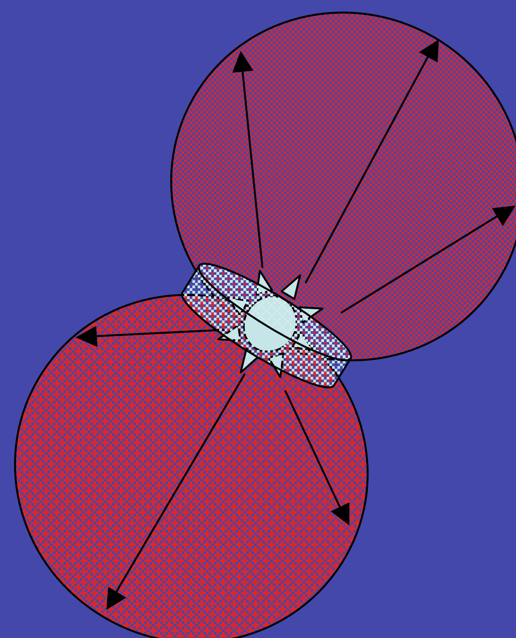
After

Precursor: Sk -69° 202 (B3Ia) in the Tarantula Nebula (massive star forming region) – *only identified SN precursor*

SN 1987a - Probing the CSM



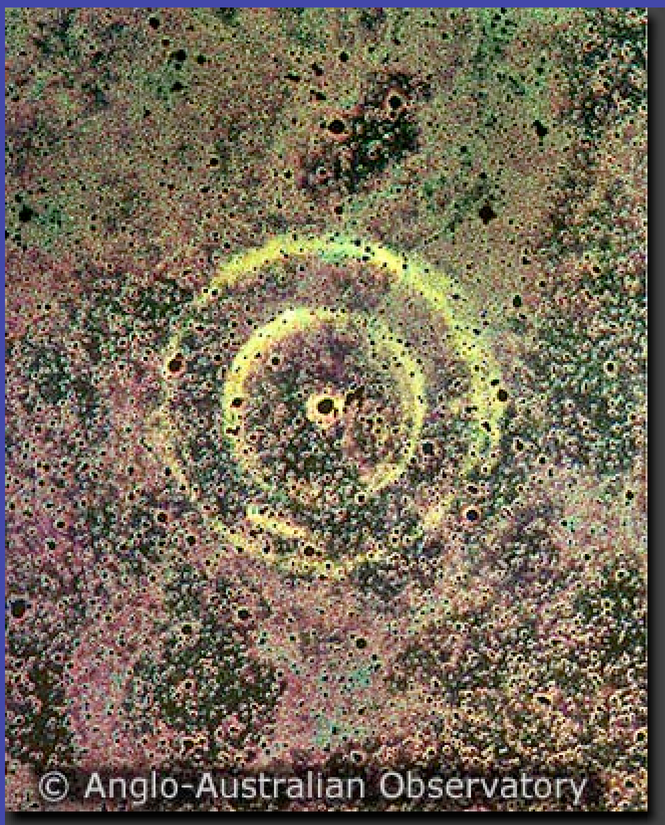
Astronomers astonished to see 3 bright rings around SN 1987a within weeks of the explosion



Rings flash-ionized by UV from burst; origin unclear (BSG wind interacting with RSG wind?)

SN 1987a - Probing the ISM

Astronomers detected light echoes from the SN



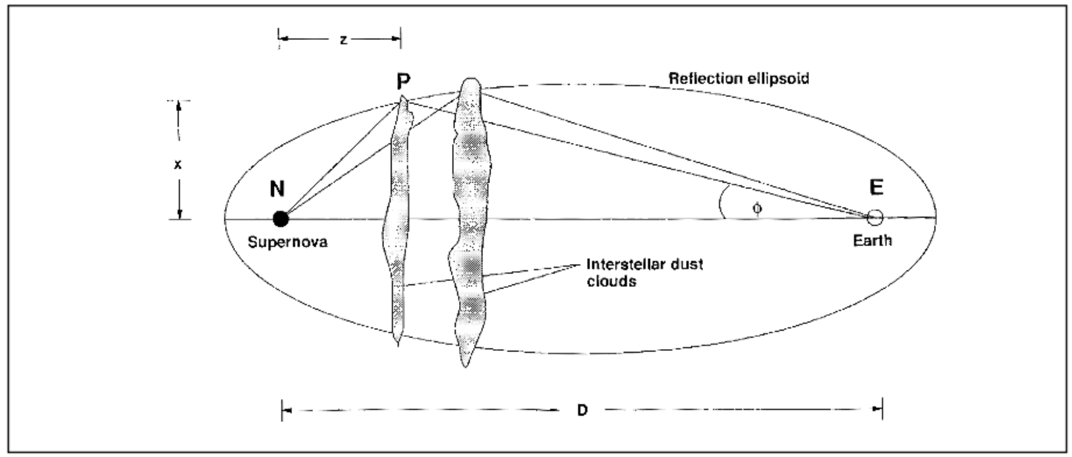
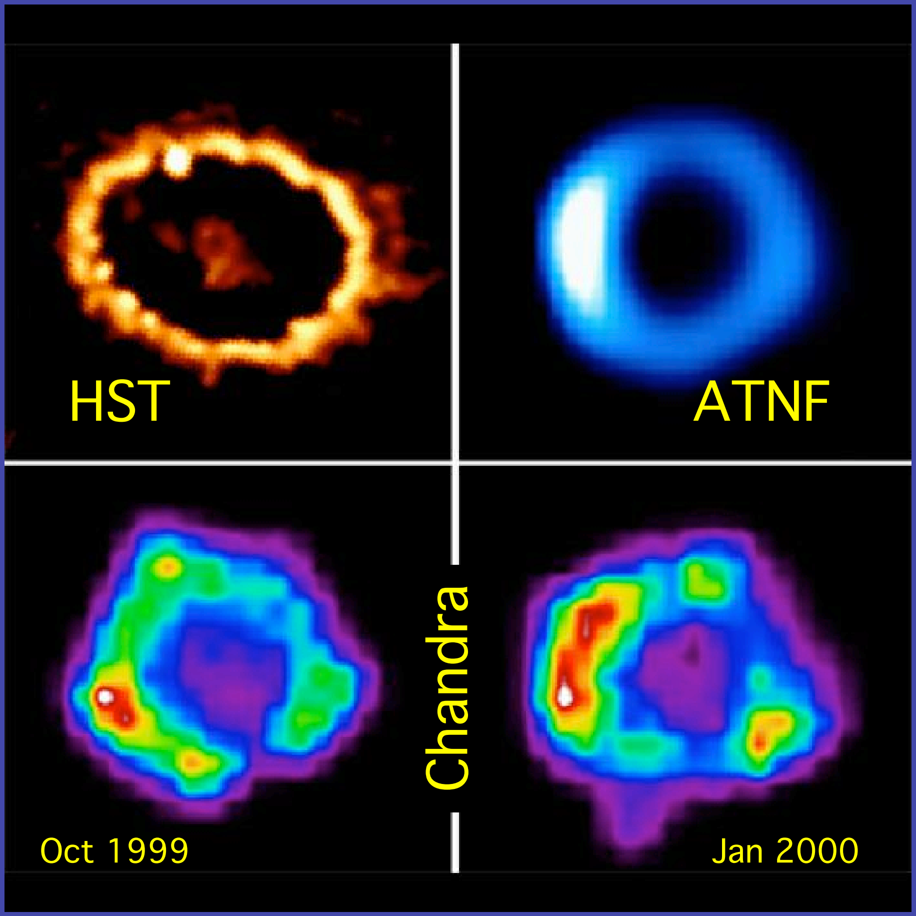


Figure 4. *A sketch of the geometry for supernova light echoes. At a given time, light from the supernova is reflected off interstellar material on the surface of an ellipsoid with the supernova (N) at one focus and the Earth (E) at the other. Light is reflected off a dust cloud at P, as described in the text. The diagram is not to scale: in reality the ellipsoid is very long and thin.*

Difference image shows light echoing off IS dust far from SN

allows investigation of dense cloud distribution along the line of sight

SN 1987a - Birth of a SNR



Blast wave from the SN is now colliding with the inner ring, producing localized brightening in the optical, radio emission, and evolving X-ray emission from the hot shocked gas.

Allows tests of SNR evolution models

SN 1987a - Probing Stellar Evolution

Core collapse supernova should produce extremely large neutrino fluxes by

$$e^- + p \rightarrow n + \nu_e$$

So neutrino flux provides a direct view of core collapse.

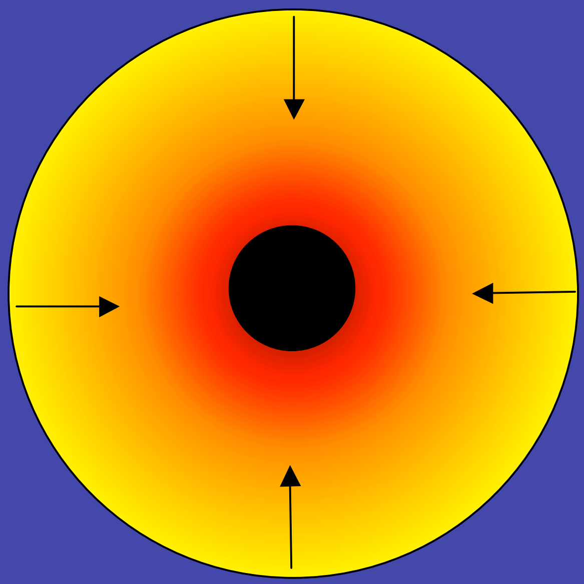
Energetics:

Radiation	10^{49} ergs
Kinetic Energy of Ejecta	10^{51} ergs
Neutrinos	10^{53} ergs

neutrinos carry almost all of the energy

Importance of Neutrinos

Key Problem: How to turn infall of envelope into outwardly expanding SNR?



Innermost layers fall onto collapsed core, and rebound, producing a shock.

Problem: Shock stalls

Solution: Neutrino flux from core re-energizes shock.

Problem: as shock moves outward, density drops, neutrino opacity drops, and shock can stall again

Regardless of the details, neutrinos can provide direct measure of the core collapse

SN 1987a - Neutrino Flux

Experiment	Feb 23, HH:MM	Number
Mont Blanc	2:53	5
Baskan	2:53, 7:36	6
Kamiokande	2:52, 7:35	12
IMB	7:35	8

Core collapse was observed to occur at 2:53 UT, Feb 23 1987.

2 bursts of neutrinos?

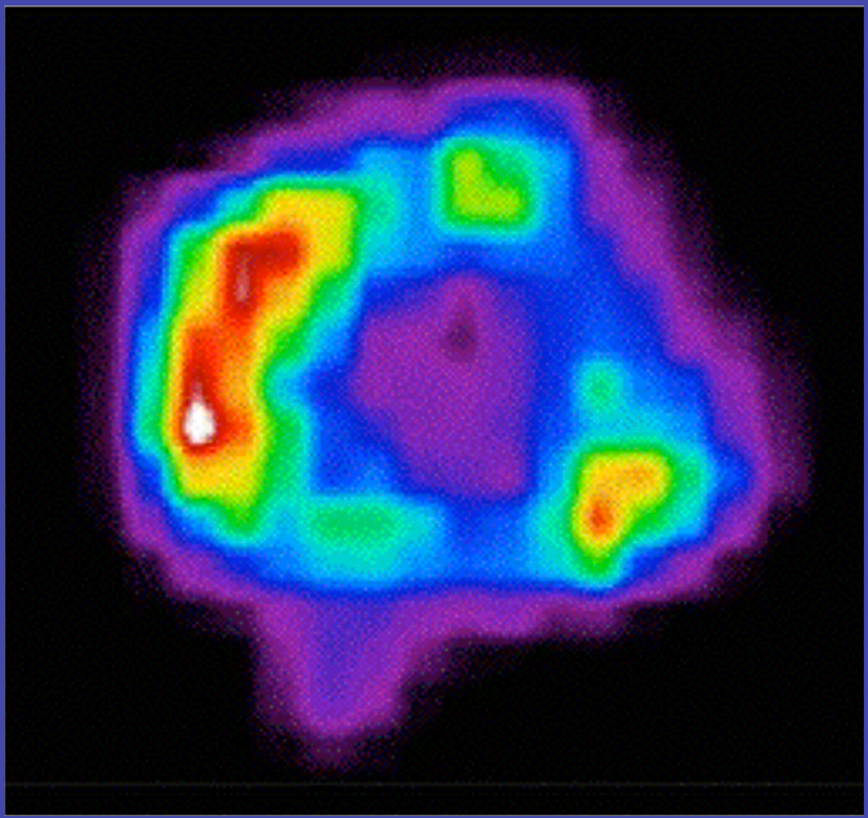
the energy emitted in neutrinos is

$$E_{\nu}^{total} = 4\pi D^2 N F \tau \ \mathrm{J}$$

where D is the distance to the LMC, N the total number of neutrinos, F the flux of neutrinos and τ the duration of the neutrino burst.

The observed energy is $E^{total} \sim 2 \times 10^{55}$ ergs!

SN 1987a - Where's the Compact Object?



Neutrino emission suggests that SN 1987a should have produced a neutron star of M_{NS}> 1.4 solar masses. It should be very hot and an X-ray source from its BB radiation

Chandra has put an upper limit on the X-ray emission of

$$L_x < 1.5 \times 10^{34} \text{ ergs s}^{-1} \text{ cm}^{-2}$$

(Parke et al. 2004)

Inner SNR too thick to see emission from the NS? or is it a black hole?

SN 1987a - Dynamics

Chandra also provides measurements of the evolution of the blast wave:

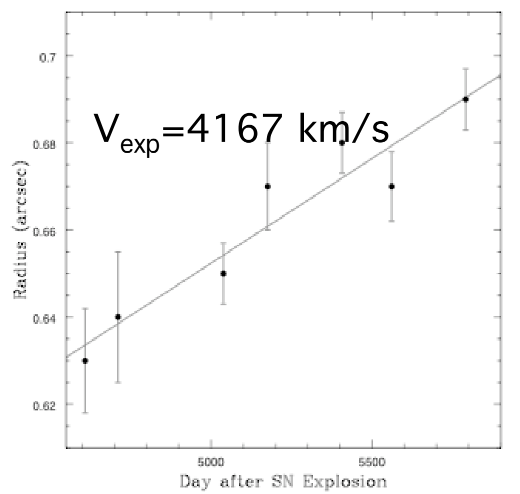


FIG. 3.—Long-term variation of the mean radius of the X-ray count distribution as obtained with a Gaussian fit. The solid line is the best-fit linear increase rate representing an expansion velocity of ~4167 km s^{-1}.

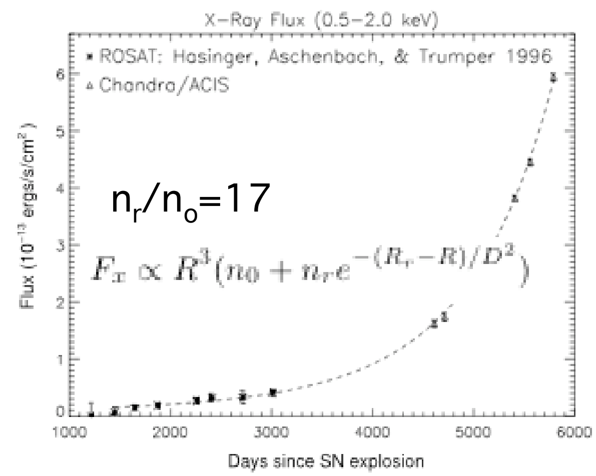


FIG. 7.—X-ray light curve of SNR 1987A. The best-fit model with an exponential density distribution is overlaid with a dashed curve.

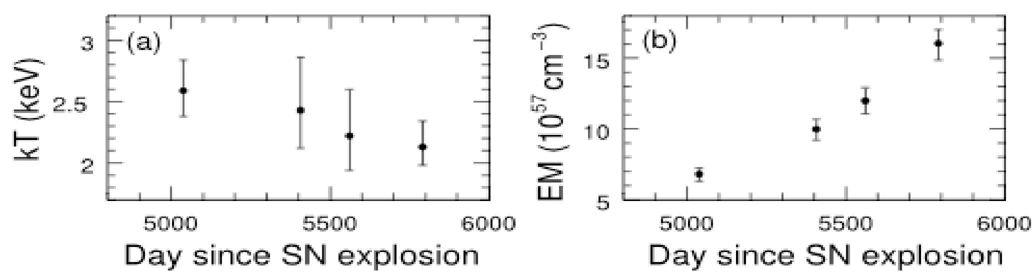


FIG. 5.—Electron temperature and the emission measure variations of SNR 1987A between 2000 December and 2002 December.

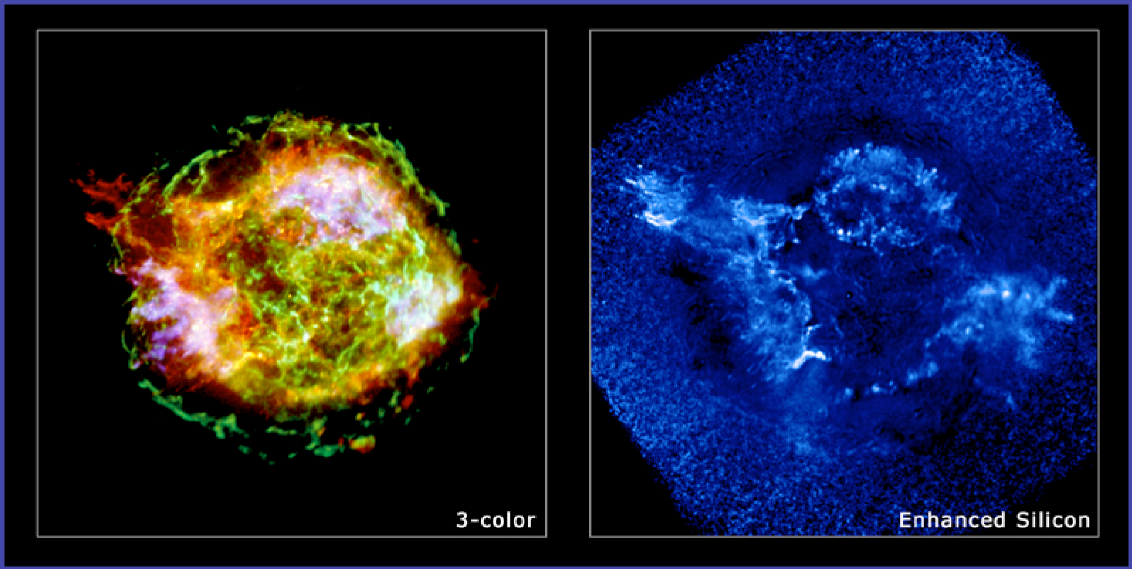
Shock cooling as it encounters denser material

Non-sphericity

Ejection of the envelope probably is not spherically symmetric.

SN 1987a: blast wave encounters eastern part of the ring before the western part

Cas A: apparent “blowouts” - a jet?



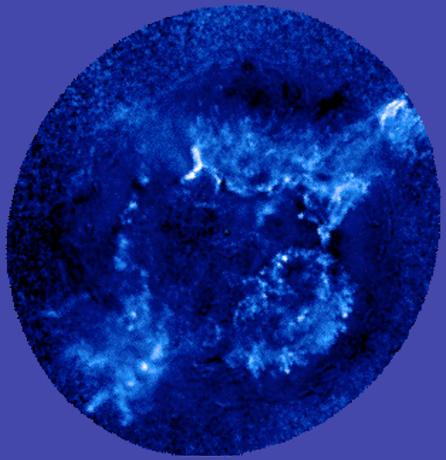
Importance of Non-Sphericity

Non-spherical explosions may help stars explode, by focussing of shock wave as a jet.

Non-sphericity might be caused by

- rapid rotation
- magnetic fields

which could cause formation of a “disk” around the collapsed core + jet



Collapsars & Hypernovae

Extremely massive stars can produce a stellar core of mass in excess of 5 solar masses. It's believed that even neutron degeneracy pressure cannot sustain it

- direct collapse to a black hole ("collapsar")

Once believed to be underluminous SN, but now thought to be able to generate extremely bright SN due to direct accretion onto the black hole: "hypernovae"

Believed related to some types of Gamma-Ray Bursts

Importance of Mass Loss

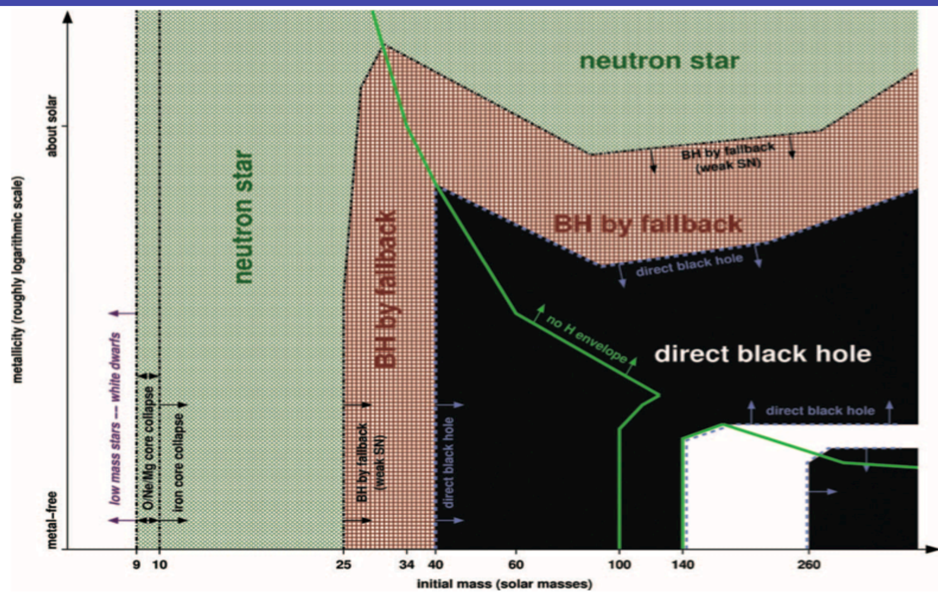
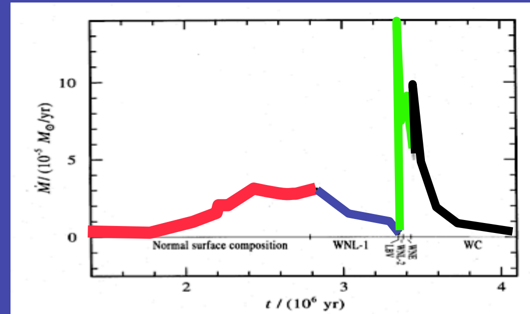


FIG. 1.—Remnants of massive single stars as a function of initial metallicity (*y-axis*; qualitatively) and initial mass (*x-axis*). The thick green line separates the regimes where the stars keep their hydrogen envelope (left and lower right) from those where the hydrogen envelope is lost (upper right and small strip at the bottom between 100 and 140 $M_\odot$). The dashed blue line indicates the border of the regime of direct black hole formation (*black*). This domain is interrupted by a strip of pair-instability supernovae that leave no remnant (*white*). Outside the direct black hole regime, at lower mass and higher metallicity, follows the regime of BH formation by fallback (*red cross-hatching and bordered by a black dot-dashed line*). Outside of this, green cross-hatching indicates the formation of neutron stars. The lowest mass neutron stars may be made by O/Ne/Mg core collapse instead of iron core collapse (*vertical dot-dashed lines at the left*). At even lower mass, the cores do not collapse and only white dwarfs are made (*white strip at the very left*).

Heger et al. 2003

Amount of mass lost by star during its life (via winds, mass transfer etc) determine the type of compact object (NS, BH or nothing).

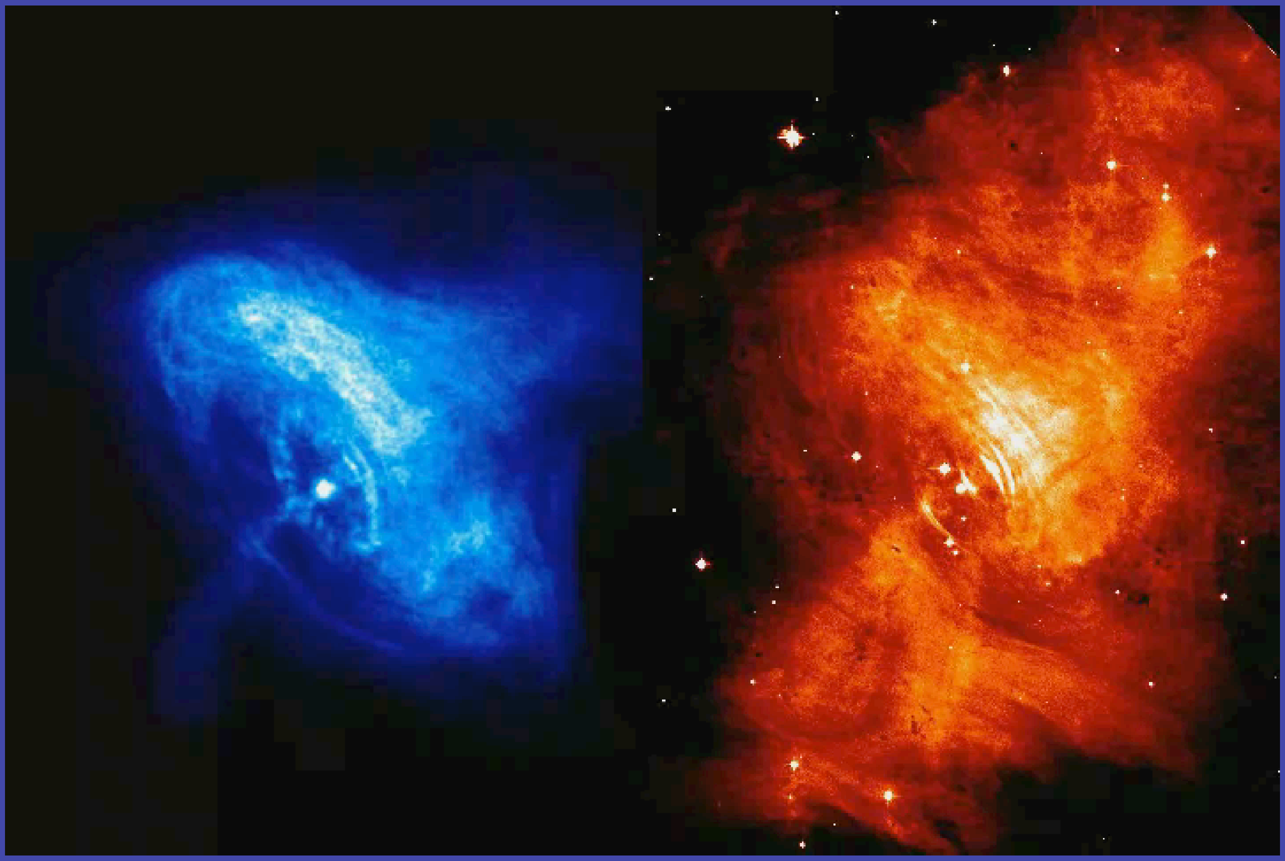


Langer et al. 1994

	M	log(t/yr)	M_{lost}	M_{end}
MS	60.0	6.5	17.6	42.4
WN	42.4	5.8	21.7	20.7
LBV	20.7	4.9	5.4	15.3
WNE/WC	15.3	5.8	11.4	3.9

SN Ibc

Interactions between the NS and CSM



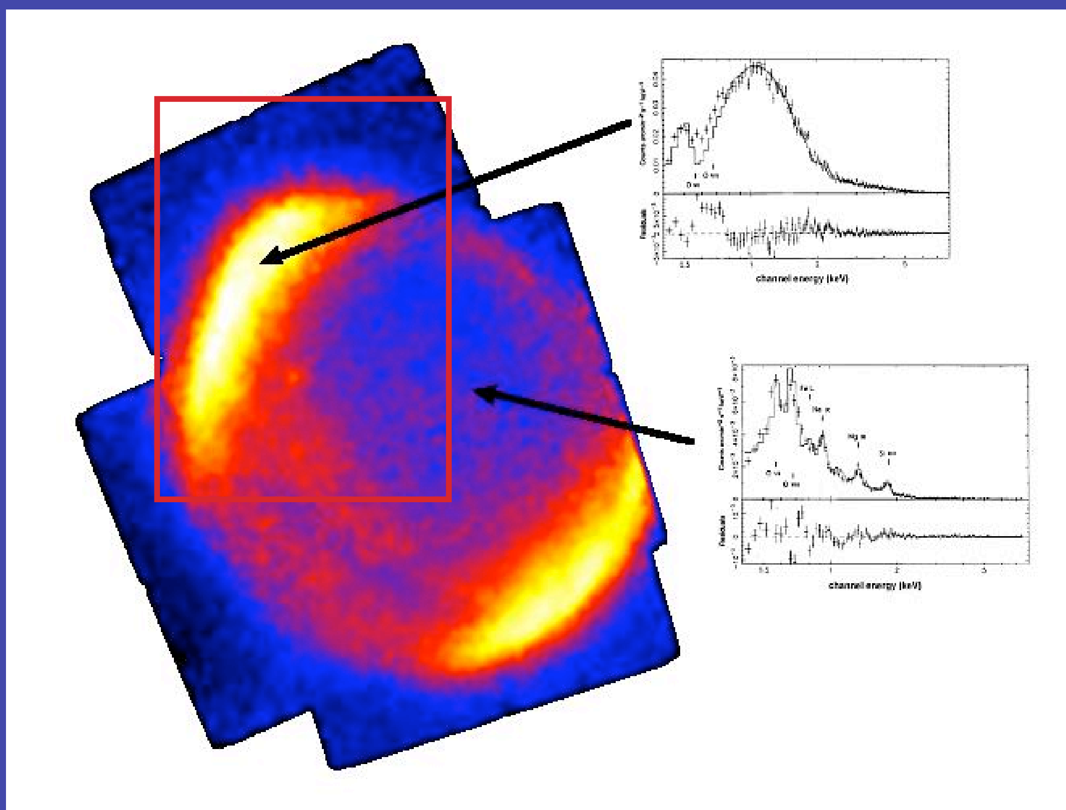
This movie shows dynamic rings, wisps and jets of matter and antimatter around the pulsar in the Crab Nebula as observed in X-ray light by Chandra (left, blue) and optical light by Hubble (right, red). The movie was made from 7 still images of Chandra and Hubble observations taken between November 2000 and April 2001. The inner ring is about one light year across.

Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

The Crab Nebula is the remnant left by the star that exploded in AD 1054

Acceleration Mechanisms

Supernova were long believed to be sources of cosmic rays (high energy subatomic particles distributed through the Galaxy). Spatially resolved X-ray spectroscopy helped prove this.

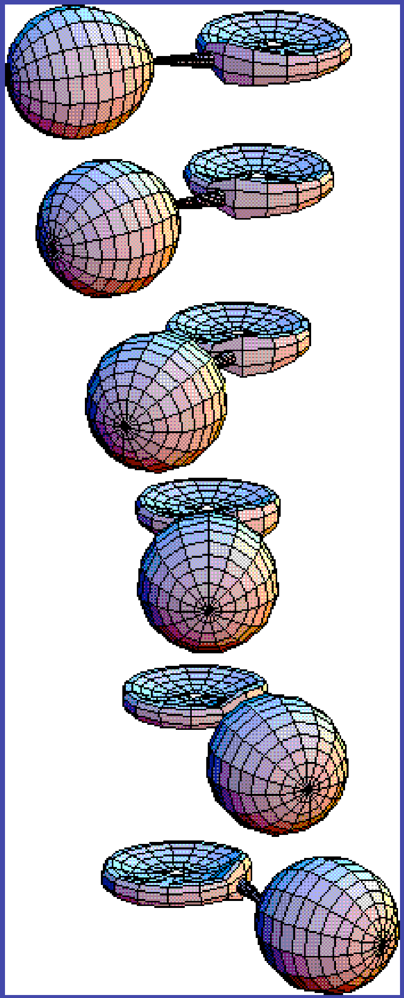


Explosions in Binaries: Novae

Semi-contact binary stars (one star fill its Roche Lobe and transfers mass to the companion) with a collapsed object (white dwarf or neutron star) as the non-contact component

Transferred material forms an accretion disk around the CO.

As material falls onto CO, it can radiate



Explosive Surface Fusion

- Material falling onto surface of the CO gets heated to extreme temperatures. Density and temperature of transferred material sufficient to allow H burning under explosive conditions (via CNO cycle in a C-O WD): a “classical nova”
- Star not destroyed.
- Novae can recur when a sufficient amount of matter transferred to the CO
- these “cataclysmic variables” are usually strong (transient) X-ray sources

Accreting White Dwarfs

White dwarfs can gain mass by RLOF from a companion star or (more slowly) from direct accretion from the ISM or direct accretion of the wind from a companion.

The "Chandrasekhar Limit" is the maximum mass that can be supported by electron degeneracy pressure and is

$$M_{ch} = 0.2(\frac{Z}{A})^2(\frac{hc}{Gm_p^2})^{3/2}m_p$$

$$M_{ch} = 1.4M_{\odot}$$

(since Z/A =0.5)

What happens if a WD accretes enough matter that its mass is higher than M_{ch}?

SN Ia

SN Ia are believed involve the destruction of a WD as it exceeds the Chandrasekhar limit, either by:

- release of gravitational energy as the WD collapses to a NS
- explosive thermonuclear fusion in a degenerate star (Hoyle & Fowler 1960)

Second mechanism is generally accepted explanation for SN Ia.

Reasons:

- Uniform lightcurve morphology powered by emission from decay of radioactive ^{56}Ni produced during the explosion
- no neutron stars for Galactic Type Ia's (SN 1006, 1572, 1604)

Standard Candles

Major goal of astronomy is to identify objects of known (or standard) brightness so that distances can be measured via the inverse-square law.

SN Ia are used as “standard candles” since:

- they can be identified as discrete events (via lightcurve and spectral signatures)
- they have nearly all the same peak brightness: $M_B \approx M_V \approx -19.3 \pm 0.3$ with very small scatter
- because they are very luminous they can be seen to the edge of the Universe

Summary:

Evolution of stars very important for understanding the evolution of the host galaxy and of the host universe

Detailed studies of supernova remnants allow direct tests of stellar evolution models and of models of envelope ejection

Outstanding questions:

- why did SN 1987a explode as a BSG instead of an RSG?
- How important are binaries?
- How “standard” are the SN Ia at high z?