

Lecture 9: Supernovae

Senior Astrophysics

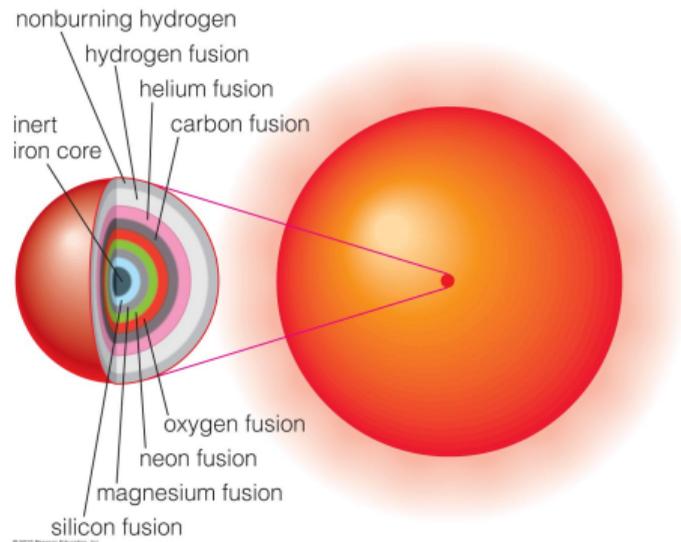
2018-03-28

Outline

- 1 Core collapse
- 2 Supernova
- 3 SN 1987A
- 4 Next lecture

Massive stars

- We have seen how massive stars (with $M_{\text{ms}} > 8-10M_{\odot}$) ignite a series of fuels up to iron, in an effort to stave off the effects of gravity. We discussed how there is no more energy to extract from fusing iron.
- At the end of this series of burning stages, an inert iron core has formed, surrounded by layers of different compositions.
- What happens next?



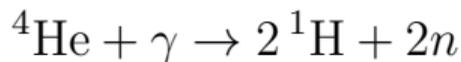
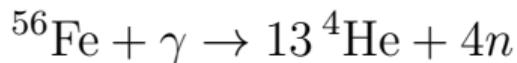
Collapse!

- The mass of Fe in the core is now about $1.2\text{--}1.4M_{\odot}$, and it must still support the weight of the rest of the star. The pressure is huge, so the atoms are degenerate: the core is, in effect, a white dwarf, embedded in the still-sputtering remnants of the star. Si in the surrounding layer continues to burn, showering Fe nuclei onto the core.
- Once the core reaches $1.4M_{\odot}$, degeneracy pressure can no longer support itself against gravity: the *Chandrasekhar limit*¹.
- Collapse begins within minutes.

¹see next lecture

Photodisintegration

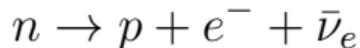
- As the collapse begins, two things happen to make it even more catastrophic. First, the temperature rises: but the Fe can't start fusing to produce more energy to halt the collapse. Instead, the iron nuclei begin to break down because of **photodisintegration**: the gamma-ray photons in the core have enough energy to destroy heavy nuclei.



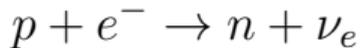
- So much of what took millions of years to produce is undone in an instant. This break-up draws even more energy from the star, which reduces the pressure, which further hastens the collapse.

Photodisintegration

- The disintegration of He produces a population of free protons and neutrons. Normally free neutrons spontaneously decay into protons via



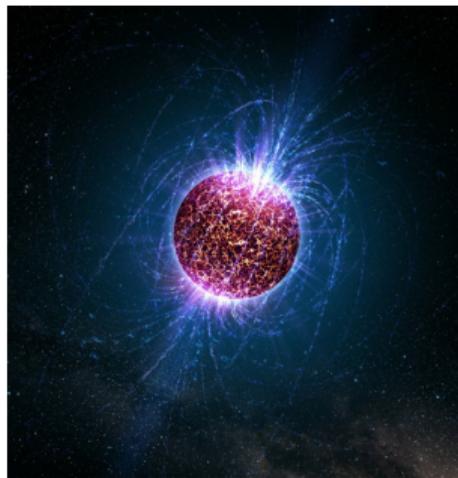
but ρ is so high in the collapsing core, the electrons are highly relativistic, and so occupy all energy states up to $\Delta E = 1.3 \text{ MeV} = (m_n - m_p)c$. Under these conditions, it is no longer energetically possible for free neutrons to undergo spontaneous decay. The reverse reaction



begins to occur spontaneously, requiring 1.3 MeV of energy for each reaction. The neutrinos escape directly from the core, and result in another large loss of energy and even faster collapse.

Neutron star

- When the whole core has been converted to neutrons and they are squeezed tightly together, *neutron degeneracy* sets in, and this time this is stiff enough to resist the gravitational pressure. Now the force of gravity is being resisted by the strong nuclear force: in essence, the whole core is like one giant atomic nucleus. A neutron star has been born.



Envelope collapse

- The core collapses on a dynamical timescale. The initial Fe core is $\sim 10,000$ km in radius with a mass $\sim 1.5 M_{\odot}$, so the dynamical time is

$$t_d \sim \frac{1}{\sqrt{G\rho}} \sim 1 \text{ sec}$$

- This is much smaller than the dynamical timescale of the rest of the star, so the core essentially collapses out from under the rest of the star. The outer layers begin falling inwards and hit the surface of the newborn neutron star.
- The details of how this happens are still unclear, but we can give a rough outline.

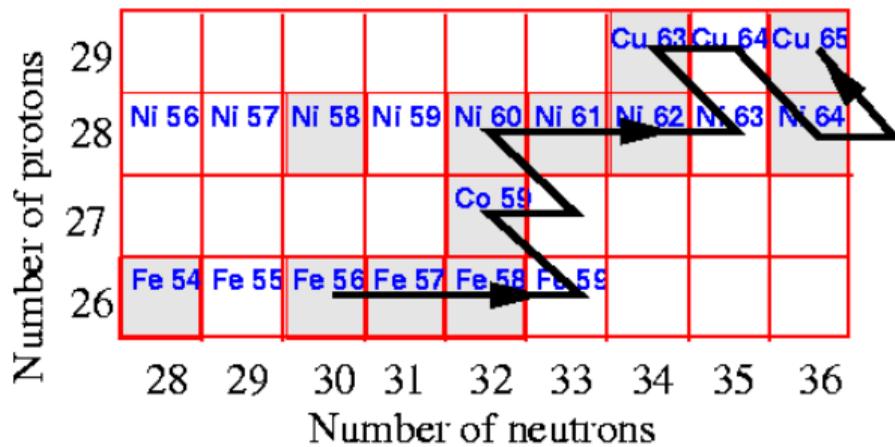
Core bounce

- When the infalling outer layers of the star meet the core they “bounce” off it so hard that they are ejected outwards again at a substantial fraction of the speed of light. This creates a blast wave which pushes the envelope back outwards at tremendous speed.
- About 0.02 seconds after the bounce, there is a traffic jam between the infalling and the outflowing gas, and the shock wave stalls. Meanwhile neutrinos are flooding out from the core, and about 1% of them get absorbed by the enormously dense material at the shock front. This reheats the material, starts violent convection above the core, and re-starts the shock (about 300 ms after collapse).

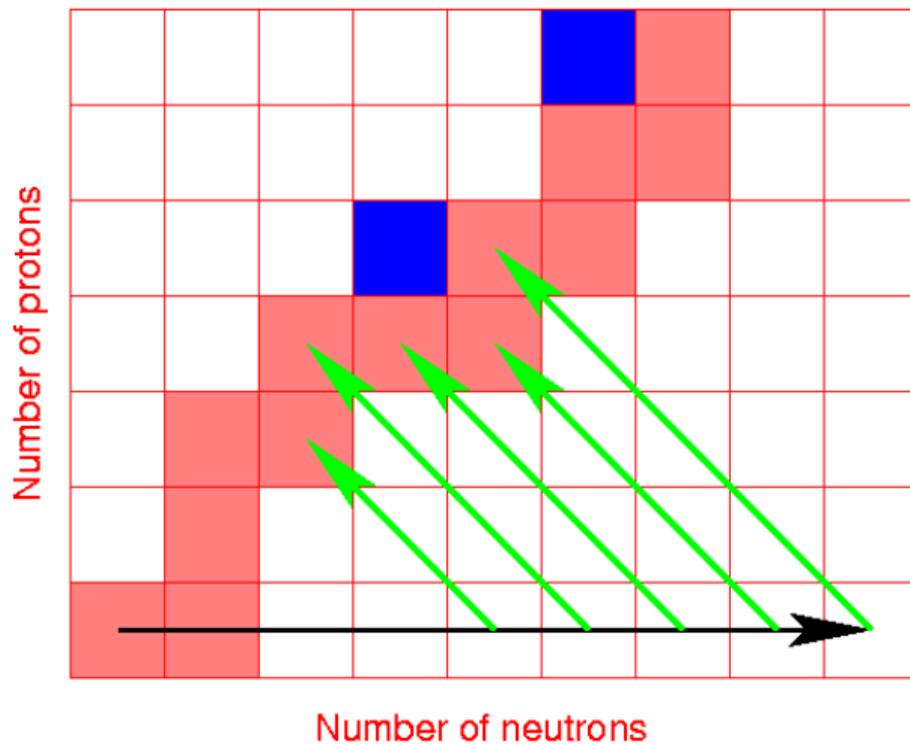
Core bounce

- This is a supercomputer animation of the collapse of the core, the stalling of the shock, and the subsequent re-start by neutrino-induced convection.

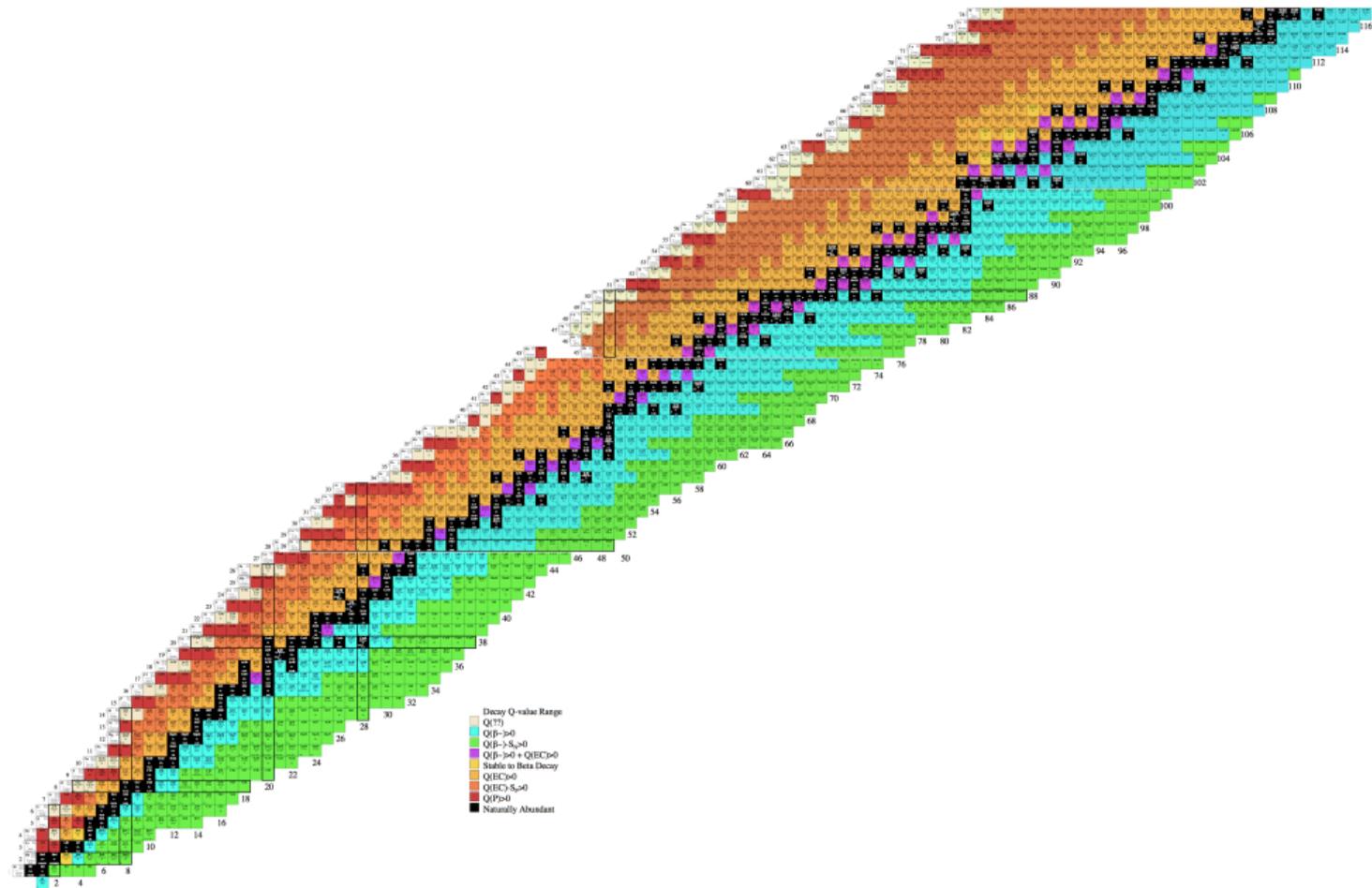
- The blast wave smashes outward through the star, travelling at about $0.1c$. Explosive nuclear fusion takes place behind the shock, and the shock violently heats and expands the layers of the star.



The *s*-process (“slow”): neutron capture followed by β -decay. Takes place in red giant stars



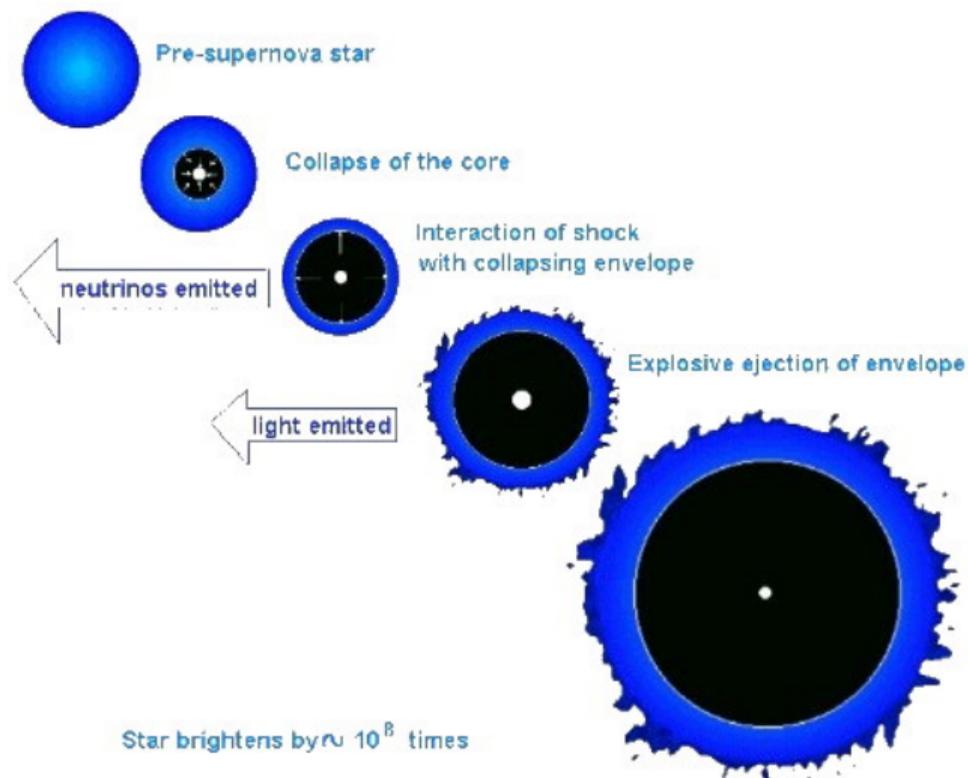
The *r*-process (“rapid”): flood of neutrons from core bombards nuclei; decay takes place after shock wave has passed.



Supernova!

- Nothing is visible from the outside until the blast wave reaches the surface of the star. Then the star becomes an enormously expanding shell of gas. Within a day, the star is an incandescent ball a billion kilometres (10 AU) in diameter. The light increases as the surface area of the ball of gas increases. After several days or weeks, the gas cools, thins, and becomes more transparent: the light from the supernova begins to drop.

Supernova!



Supernova!



SN1994D in NGC 4526

Energy budget

grav. energy released	ΔE_{grav}	$3 \times 10^{46} \text{ J}$	
<hr/>			
photodisintegration + neutron formation	ΔE_{nuc}	$2 \times 10^{45} \text{ J}$	$\sim 0.067 \Delta E_{\text{grav}}$
ejecting envelope	ΔE_{bind}	$5 \times 10^{44} \text{ J}$	$\sim 0.017 \Delta E_{\text{grav}}$
KE of envelope	ΔE_{kin}	$1 \times 10^{44} \text{ J}$	$\sim 0.003 \Delta E_{\text{grav}}$
radiation	ΔE_{rad}	$1 \times 10^{44} \text{ J}$	$\sim 0.003 \Delta E_{\text{grav}}$
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total			$\sim 0.09 \Delta E_{\text{grav}}$

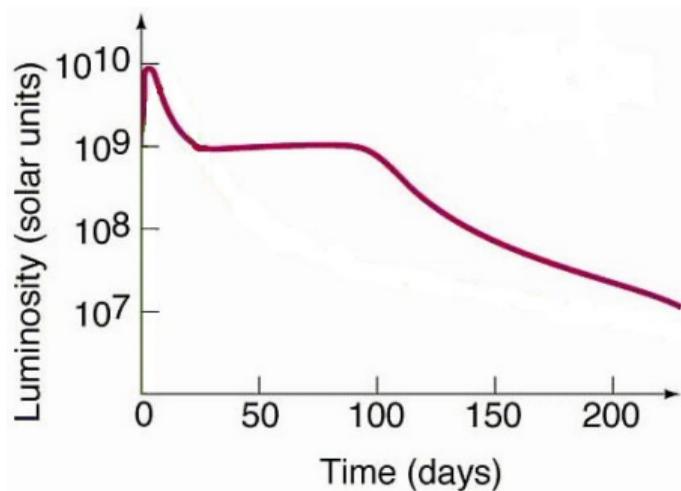
Where does the rest of the energy go?

Energy budget

- The answer is that it is radiated away as neutrinos. When the protons in the core are converted to neutrons, neutrinos are produced, which carry away the vast majority of the energy with them. The explosion we see uses only $\sim 1\%$ of the energy, but that is more than enough to blow up the star.

SN light curve

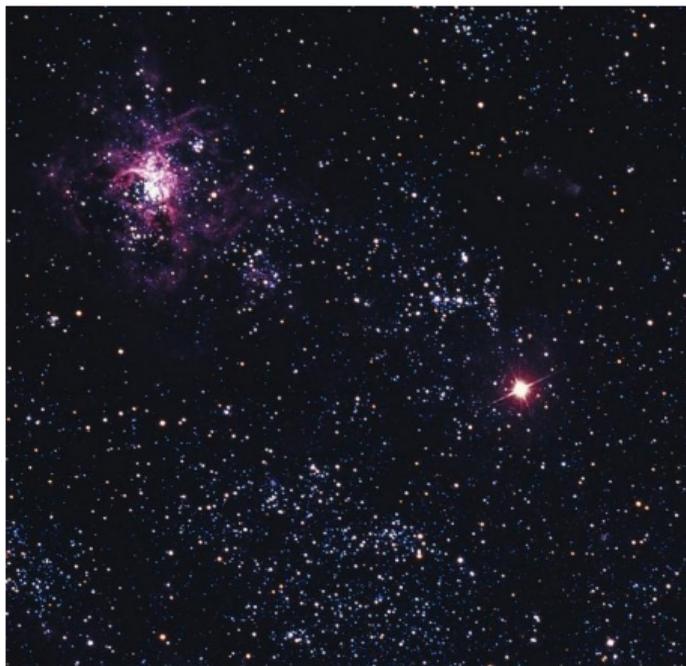
- The decline in brightness tapers off, however, to a slow exponential decrease. Radioactive elements formed in the blast (principally Ni and Co) begin to decay, and the energy release heats the surrounding debris. This produces a “bump” in the light-curve, where the decay in brightness slows down or halts for some weeks.



Type Ia (thermonuclear) supernovae

- It happens that there is a whole class of supernovae which do not show this “bump” in the light curve. We believe these are a completely different type of explosion: instead of representing the death of a massive star, they result from the collapse of a white dwarf in a binary system.
- We will discuss these supernovae later in the course.

Supernova 1987A

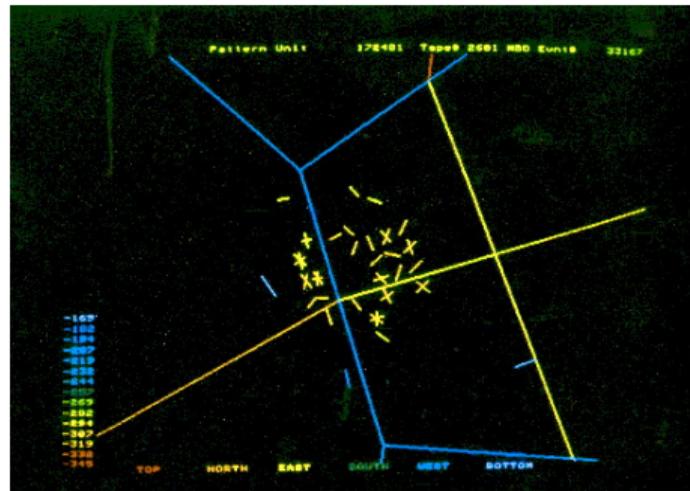


Supernova image from March 1987: image by Marcelo Bass,
CTIO/NOAO/AURA/NSF,
http://www.noao.edu/image_gallery/html/im0644.html

- On 23 February 1987, the nearest supernova to earth since Kepler's supernova of 1604 exploded in the Large Magellanic Cloud.

Neutrinos

The first detection of the new supernova was actually made by two *northern* hemisphere observatories. The Kamiokande experiment in Japan and the IMB experiment in Ohio both detected a burst of neutrinos associated with the supernova: 12 and 8 events respectively, observed some hours before the optical supernova was spotted.



One of the neutrino events from the IMB detector. The neutrino produced a flash of light, which was detected by several photo-multiplier tubes: by noting which PMTs responded, the direction and energy of the original neutrino can be deduced. (From <http://www-personal.umich.edu/~jcv/imb/imbp5.html>)

SN1987A

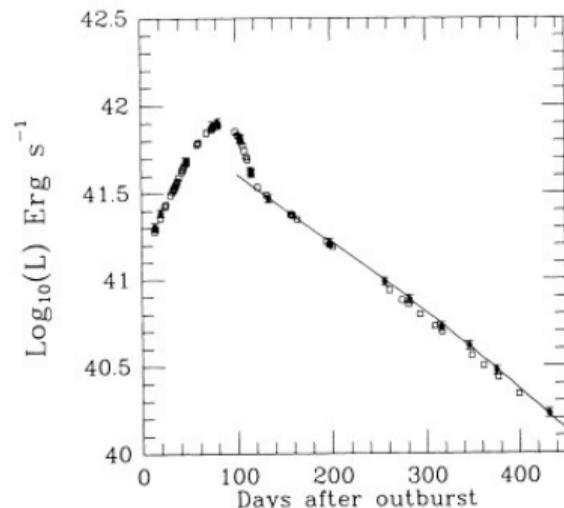
Three hours after the neutrino detection, the first visible light reached Earth. It was seen independently by at least four observers, in Chile, New Zealand and South Africa on the evening of 24 February 1987.



AAT image of the supernova, about two weeks after discovery.

Light curve

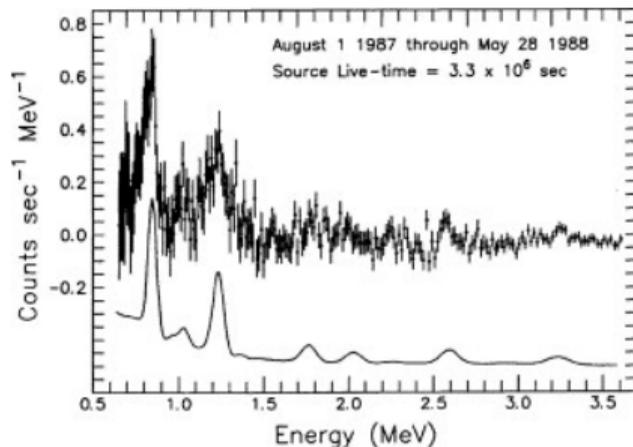
- The light-curve behaved exactly as expected: after the initial increase, it faded quickly until June 1987. Then it settled into a much slower fade, of about 1% a day, for two years.
- This corresponds exactly to the laboratory-measured half-life of ^{56}Co (77 days), which is the result of the (rapid) decay of ^{56}Ni which is produced in the blast. We could even determine the mass of nickel produced: about $0.08 M_{\odot}$, or about 1% of the mass of the core just prior to the explosion.



Bouchet et al. 1991, A&A 245 490

Light curve

- What's more, several satellites detected gamma-ray emission lines from ^{56}Co , which was clinching proof that the radioactive cobalt was made in the supernova itself.



The gamma-ray spectrum of SN 1987A, compared with models for the ^{56}Co lines.

Progenitor

Several aspects of the explosion came as an enormous surprise. First, and most importantly, astronomers were able to definitively identify the progenitor star from pre-supernova images.

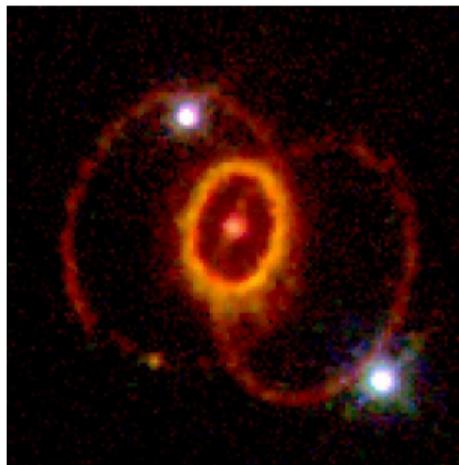
Disconcertingly, the star, Sk $-69^{\circ} 202$, was a *blue* supergiant instead of a red one. The fact that the star had disappeared after the explosion was clinching proof.



Rings

Several years later, HST obtained images of SN1987A, showing an amazing system of three rings of glowing gas. There is an inner equatorial ring, and two outer rings which are almost co-axial with the inner ring but on either side of the equatorial plane, and about 2.5 times larger than the inner ring.

It appears that the rings must have been ejected in two episodes of violent mass loss, one about 20,000 years (the outer rings) and one about 10,000 years (the inner ring) before the supernova explosion.

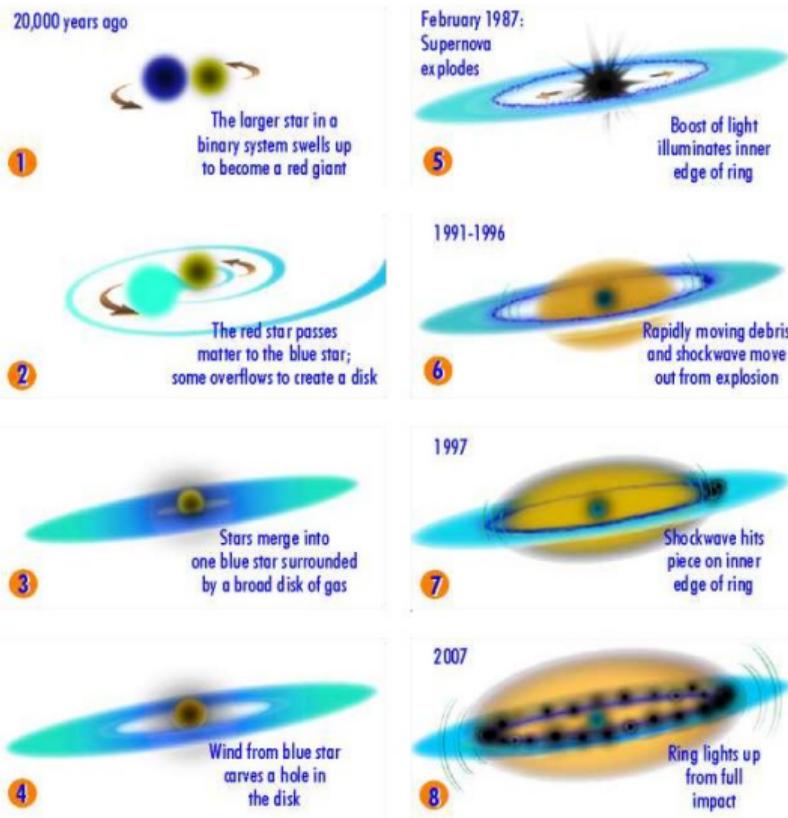


Rings

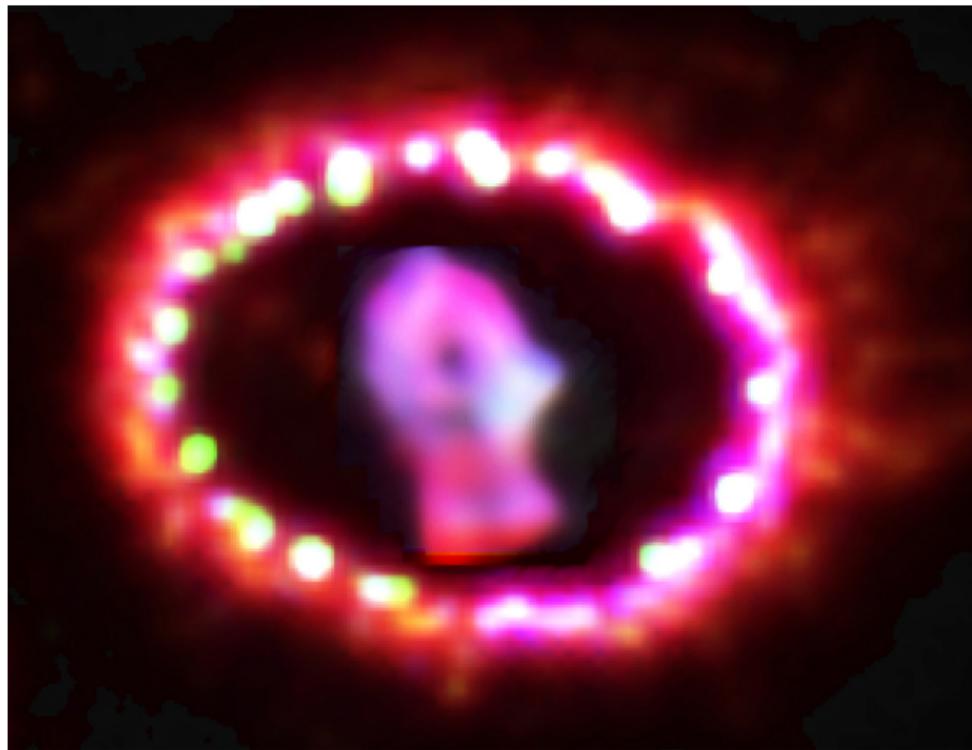
Progenitor

- These rings, and some observed chemical anomalies, suggest that the progenitor was in a binary system, and either accreted large amounts of material from its companion, or (more likely?) merged with the companion completely. The companion star dissolves completely in the primary's envelope. Because of the added mass and dredge-up of material, the progenitor turns into a blue supergiant.
- The following sequence shows one possible scenario for the creation of the ring around SN 1987A.

Formation scenario



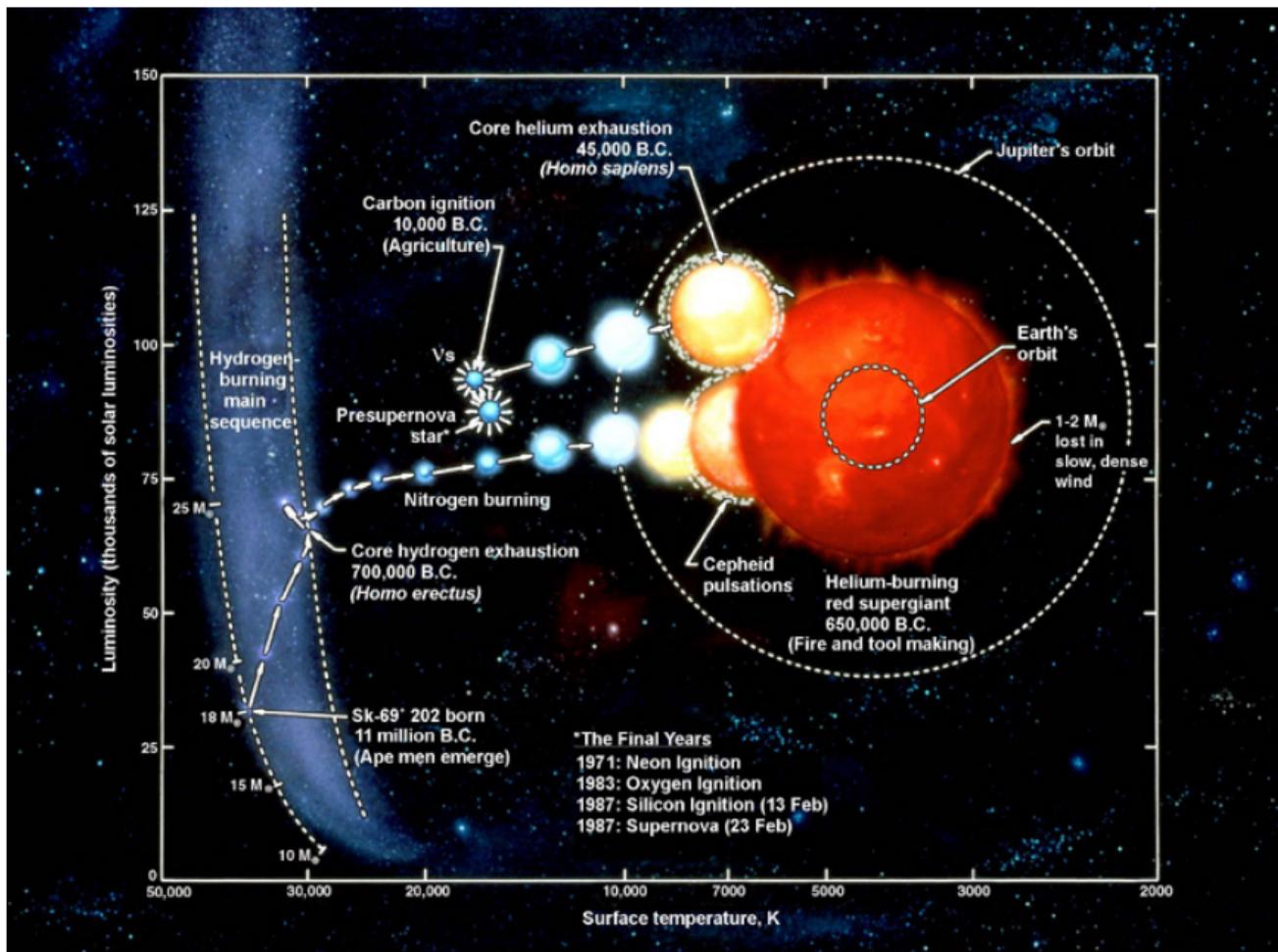
Progenitor



The most recent Hubble picture of SN1987A's rings, from June 2011. The expanding supernova remnant is now clearly visible inside the ring.

Remnant

Despite intensive searching, the stellar remnant left behind has still not been found. It is presumably either a neutron star or a black hole, but for whatever reason, it is not yet visible.



Next lecture

- NO LAB today (or Friday)
- Next lecture (after the break): Stellar remnants
 - White dwarfs
 - Neutron stars
 - Black holes