The structure and evolution of stars

Lecture13: Supernovae - deaths of massive stars

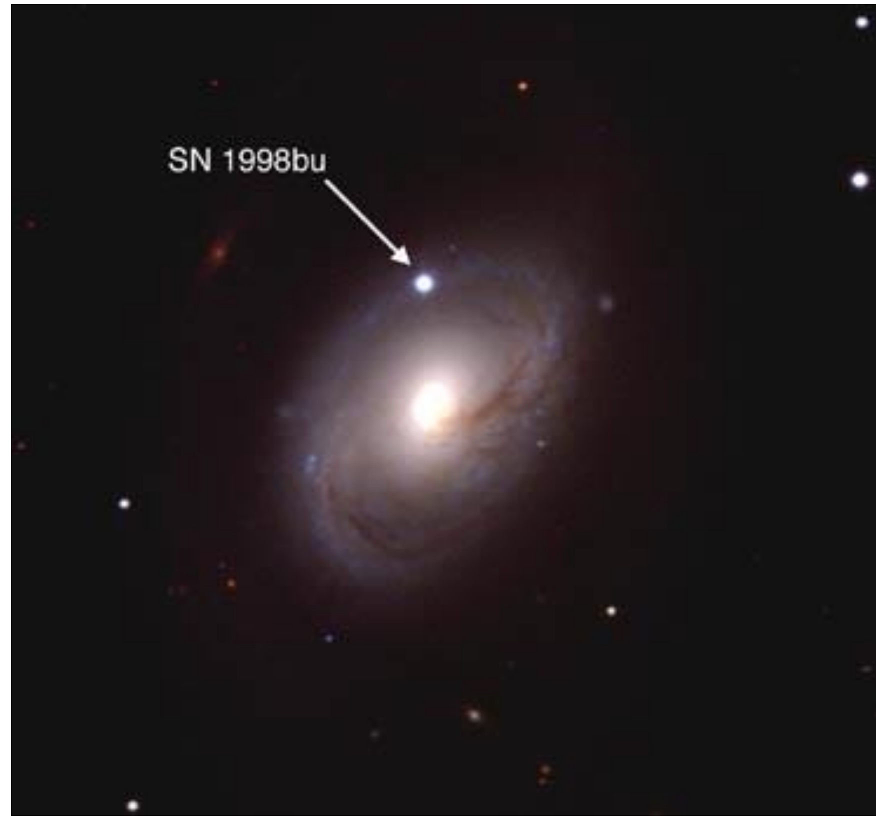
Learning Outcomes

In these final two lectures the student will learn about the following issues:

- What is a supernova
- Brief historical story of discovery of supernovae
- The difference between Type I and Type II supernovae
- The two physical mechanisms for producing supernovae
- The meaning of the terms core-collapse supernovae and thermonuclear supernovae
- What stars produce the typical Type II and Type Ia
- The best studied supernova - SN1987A
- Surveys of supernovae in the distant Universe - using Type Ia supernovae to measure the expansion of the Universe

What is a supernova ?

Stars which undergo a tremendous explosion, or sudden brightening. During this time their luminosity becomes comparable to that of the entire galaxy (which can be ~10^{11} stars)



SN1998bu in M96: left DSS reference image (made by O.Trondal), right BVI colour image from 0.9m at CTIO (N. Suntzeff)

Supernovae

In the 1930’s ***supernovae*** were recognised as a separate class of objects to ***novae*** (meaning new stars).

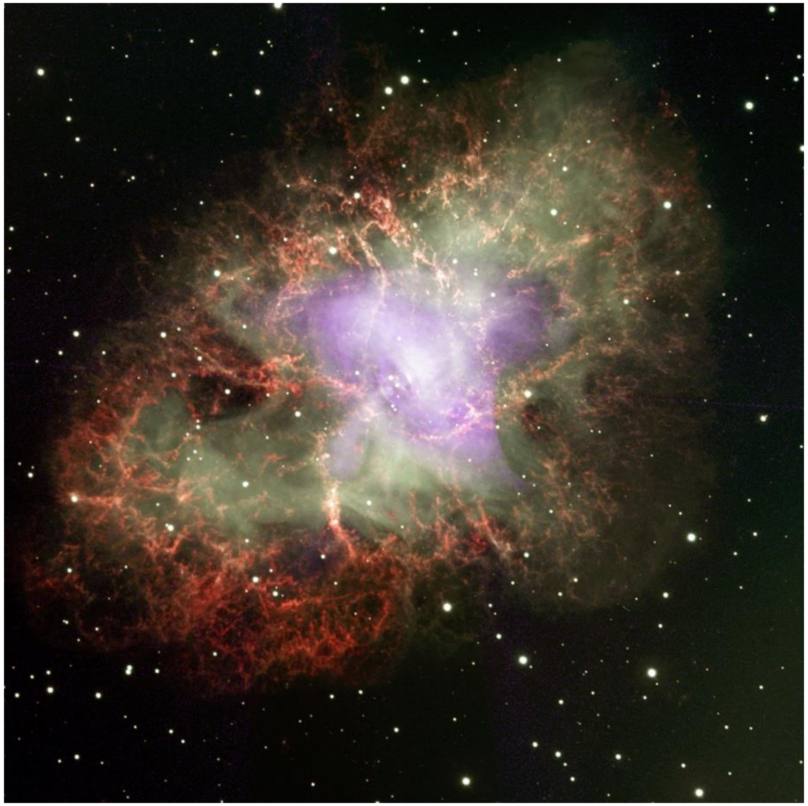
- So-called by Fritz Zwicky, after Edwin Hubble estimated distance to Andromeda galaxy (through Cepheids)
- Hence the luminosity of the “nova” discovered in 1885 in Andromeda was determined
- Supernovae outbursts last for short periods: typically months to a few years
- Typical galaxies like the Milky Way appear to have a rate of 1-2 SNe per 100 years
- But as they are extremely bright - even small telescopes can detect the, a large cosmic distances (we shall derive detection volumes for the different types)
- Historical accounts of supernovae in our galaxy are coincident with supernovae remnants now visible

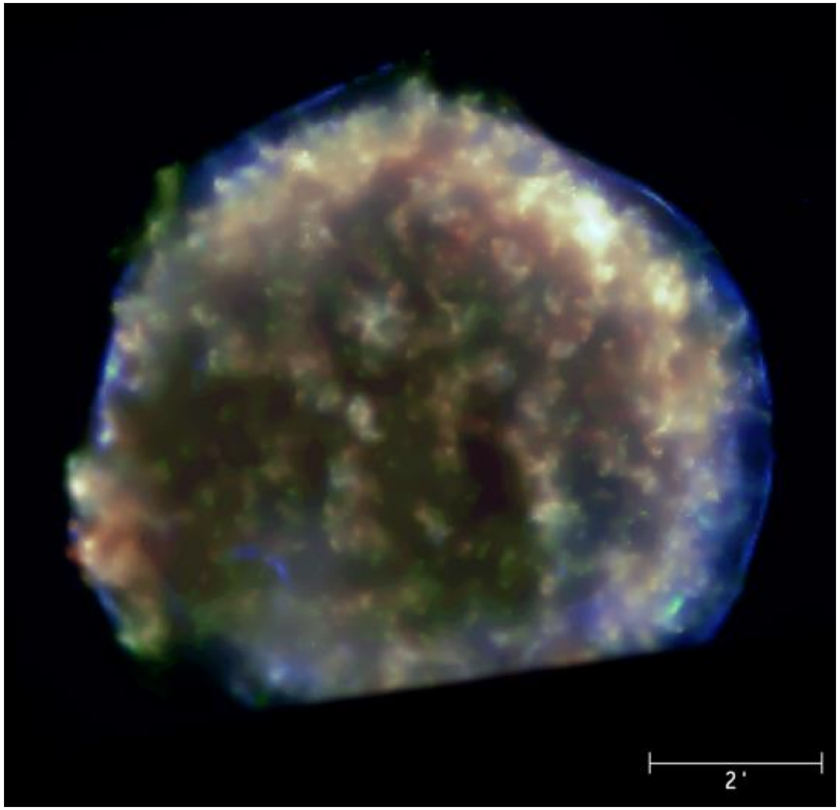
Supernovae in the Milky Way

European and far eastern written records of the following Galactic events:

Supernova Remnant	Year	Peak Visual mag
CasA	1680	?
Kepler	1604	-3
Tycho	1572	-4
3C58	1181	-1
Crab	1054	-4
SN1006	1006	-9

- Supernova remnants observable in optical, radio and X-ray for thousands of years
- Catalogues of Galactic SNR: Dave Green (Cambridge) http://www.mrao.cam.ac.uk/surveys/snrs/





The Crab nebula - optical (red) and X-ray (lilac) composite

Death of a massive star

Tycho's supernova remnant in X-rays

Explosion of a white dwarf

The observed types of supernovae

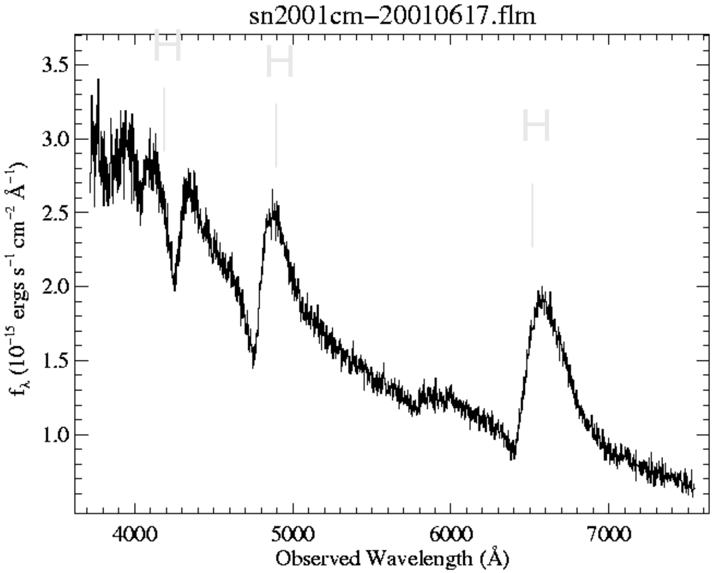
Supernovae explosions classified into two types according to their *observed* properties. The two main types are ***Type I*** and ***Type II*** which are distinguished by the presence of hydrogen lines in the spectrum.

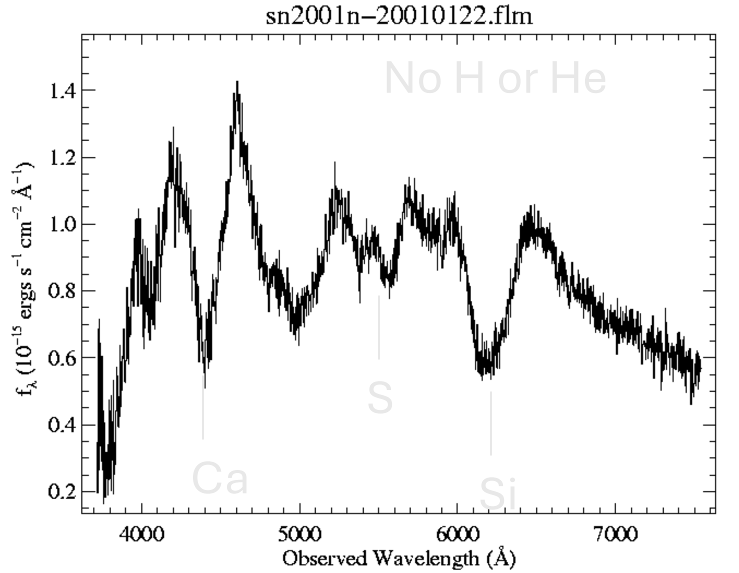
No hydrogen → Type I

- Si → Ia
- He → Ib
- He or Si → Ic

Hydrogen lines → Type II → Lightcurve and spectra properties → II-P, II-L, IIn, IIb, II-p

Example spectra of Type Ia and Type II SNe





Typical Type II SN observed within a few weeks of explosion

Typical Type Ia supernova observed near maximum light (i.e. when SN is at its brightest)

Core collapse - the fate of massive stars

All types of SNe apart from Type Ia are not observed in old stellar populations (such as elliptical galaxies). In particular Type II are observed mostly in the gas and dust rich arms of spiral galaxies. Star formation is ongoing and young stars are abundant. By contrast Type Ia SNe are found in all types of galaxies.

Hence the strong circumstantial evidence suggests:

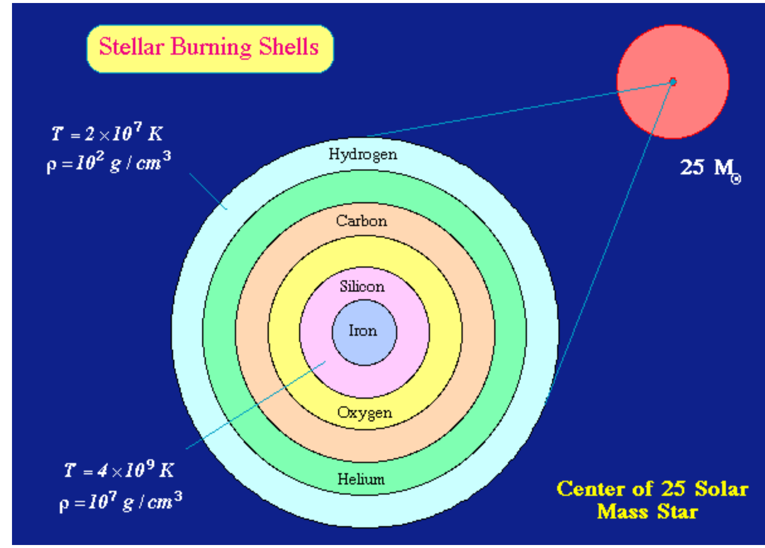
- Type II supernovae are associated with the deaths of massive stars - the collapse of the Fe core at end of evolution
- These stars have large H-rich envelopes, hence the presence of H in the spectra

Stellar evolutionary calculations suggest:

- Stars with $M_{MS} > 8\text{-}10 M_{\odot}$ undergo all major burning stages ending with growing Fe core.
- Core surrounded by layers of different compositions
- The Fe core will no longer be able to support the outer layers - we call these supernovae progenitors

Fe core contracts as no nuclear fusion occurring, and e^- become degenerate gas.

When core mass > M_{Ch} the e^- degeneracy pressure is less than self-gravity and core contracts rapidly (for Fe M_{Ch}~1.26 $M_\odot$)



Result:

- Gas is highly degenerate, hence as core collapses *T* rises unconstrained, and reaches threshold for Fe photodisintegration

$$^{56}Fe \rightarrow 13\,^4He + 4n - 100\mathrm{MeV}$$

- Reaction is highly endothermic - collapse turns into almost free fall.

Infall continues, T rises, and photon field energetic enough to photodissociate

$$He \rightarrow 2n + 2p - 25MeV$$

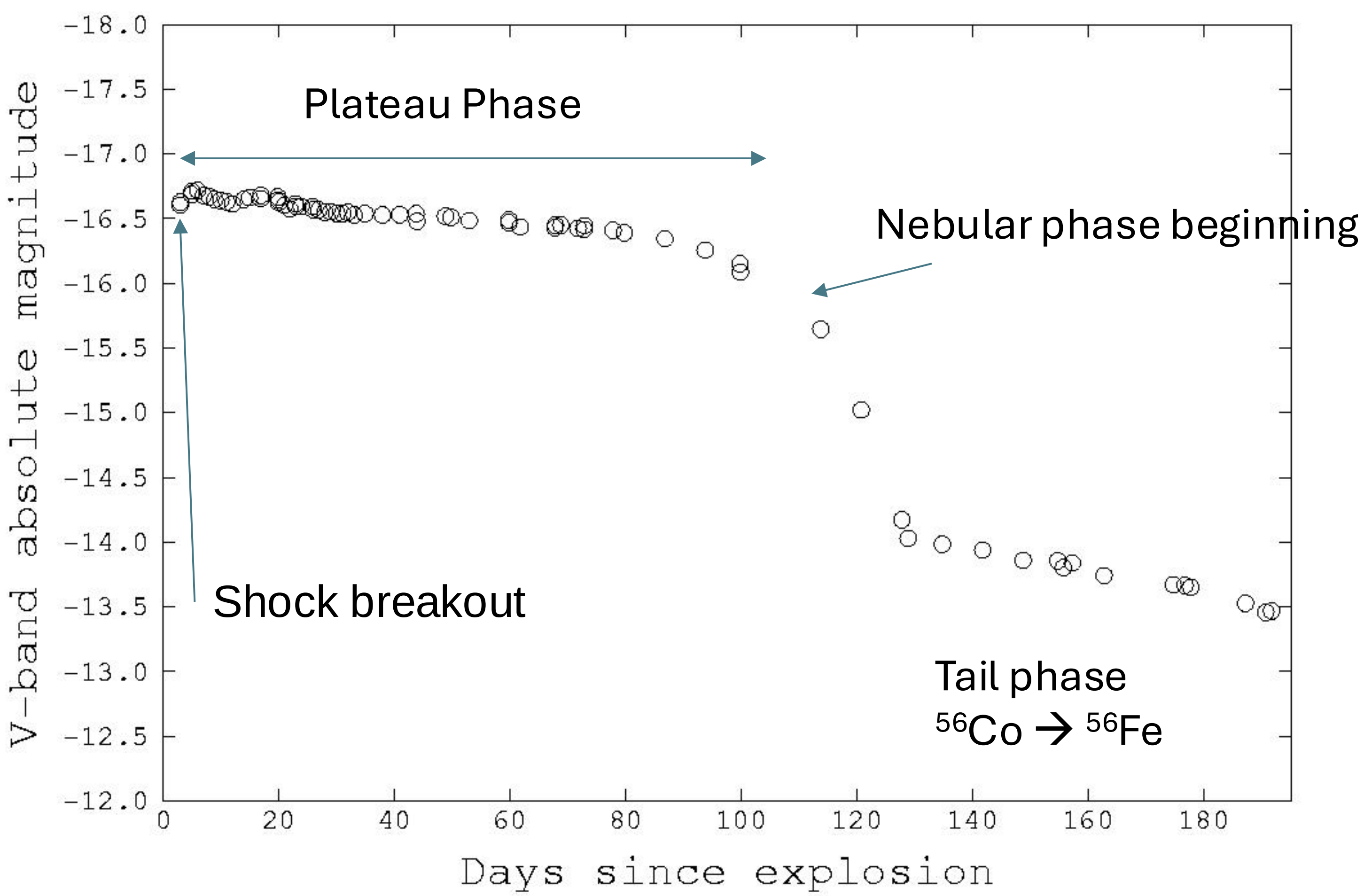
- Core contracts further, density becomes high enough for e^- capture

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

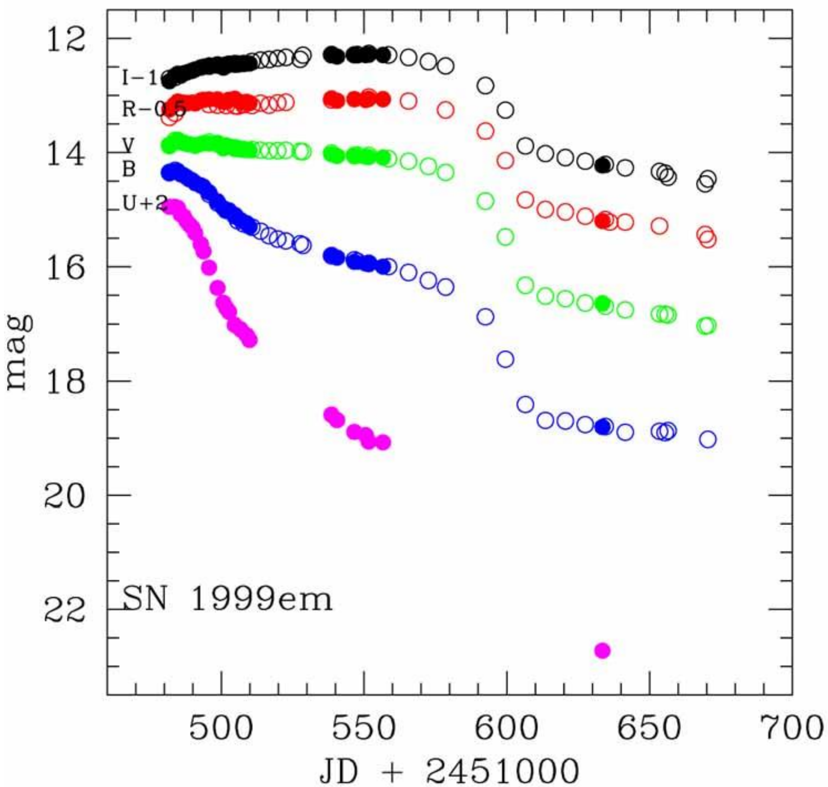
- The neutron gas becomes degenerate at densities of ~10^{18} kg m^{-3} neutron star created.

Observed properties of a Type II SNe

Lightcurve of a typical Type II supernova - SN1999em (Hamuy et al. 2001)

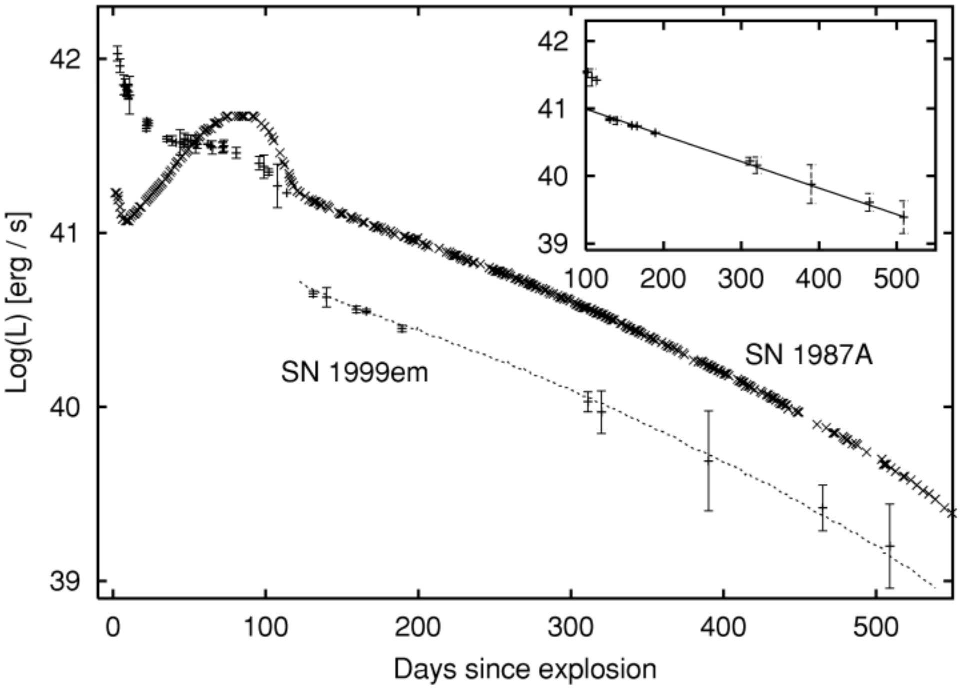


From Hamuy et al. 2001, ApJ



The *UBVRI* lightcurves of SN199em. Showing the temporal behaviour of the supernova at different wavelengths.

From Elmhamdi et al. 2003, MNRAS



Bolometric luminosity of SN1999em composed by summing all the flux within the *UBVRI* bands. The panel shows the flux scaled by a factor 1.55, which accounts for estimated flux in the infra-red. The straight-line is a fit for the radioactive decay of 0.02 $M_\odot$ of ^{56}Ni. The famous SN1987A is shown for comparison

The explosion energy budget

How is the explosion driven by the collapse of the core ?

What happens to the outer layer of the star during and following the few tenths of a second after core collapse ?

Energy source	Energy
Gravitational potential energy available from collapsing core	**Approx 3×10^{46} J**
Energy absorbed in Fe photodisintegration to p+n	-2×10^{45} J
Radiated energy over τ_{SN}	-3×10^{44} J
Energy required to eject loosely bound envelope	-5×10^{44} J
Kinetic energy of the envelope ($v_{exp} \sim 10^4$ kms^{-1})	-10^{45} J
Sum of observable energy	**Approx -3×10^{45} J**

Neutrino driven explosions

Only 1% of energy is "visibly" accounted for.

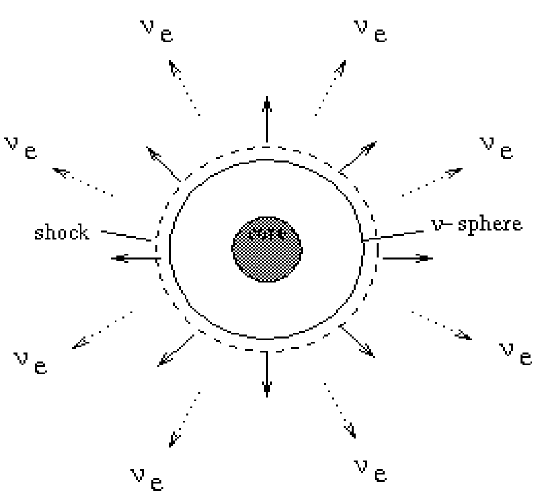
Two stages of collapse:

- Dynamic stage (collapse, neutronization) – only ν_e are emitted, accounting for carry 1-3% of the binding energy (duration - 10 ms).
- Cooling stage – all neutrino flavours are emitted which carry (96-98)% of binding energy, duration - about 10 s.

$$e^- + e^+ \rightarrow \nu + \bar{\nu}$$

$$e^- + \gamma \rightarrow e^- + \nu + \bar{\nu}$$

$$e^- + nucleon \rightarrow e^- + \nu + \bar{\nu} + nucleon$$

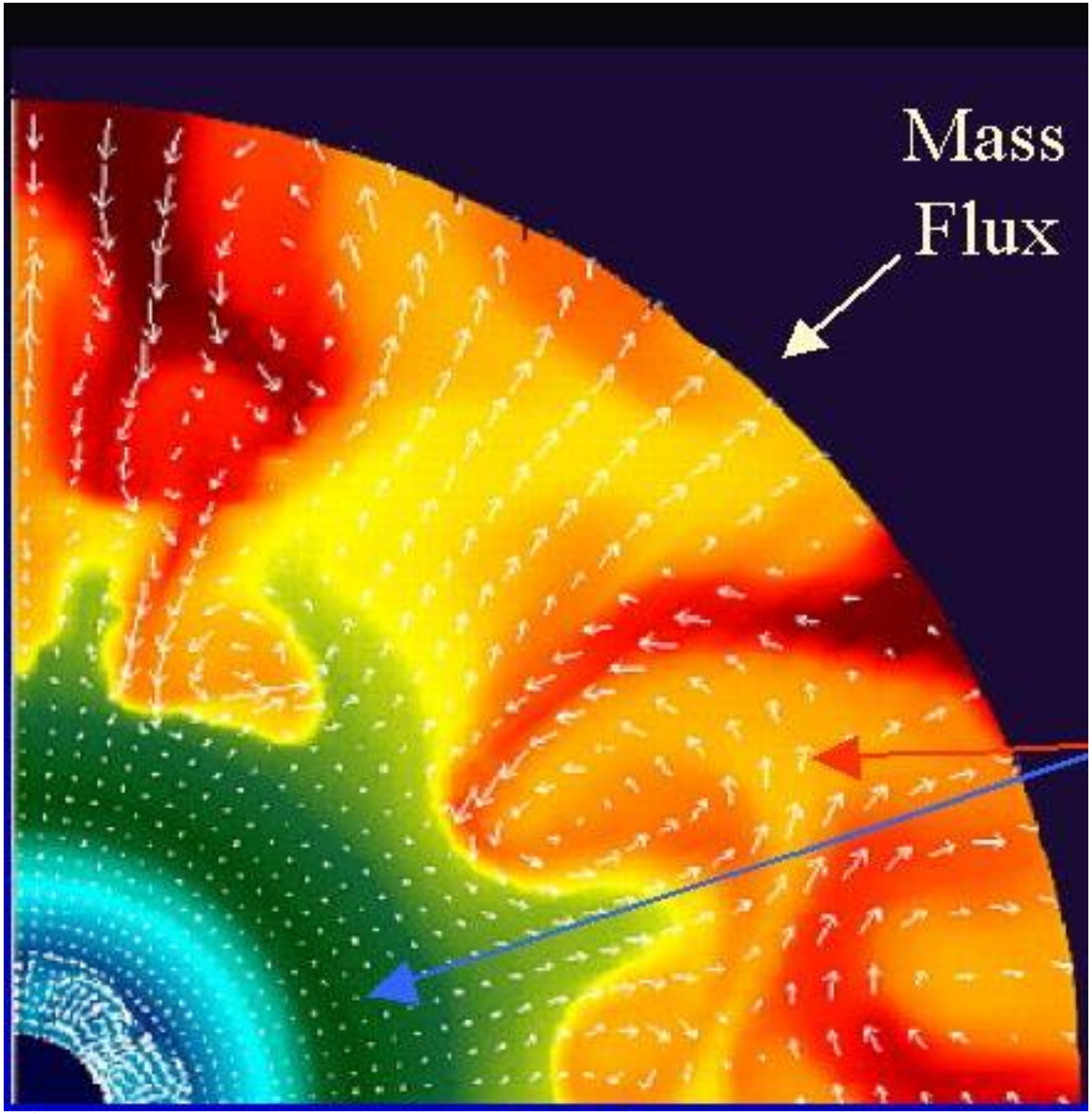


If a fraction of their energy is deposited in the surrounding mantle or envelope, neutrino energy could drive the supersonic shock wave and explosion

300km

100km

60km



Dense core

Neutrinosphere

Net heating

Janka & Mueller (1996):
Neutrino energy deposition and neutrino energy spectrum ?

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

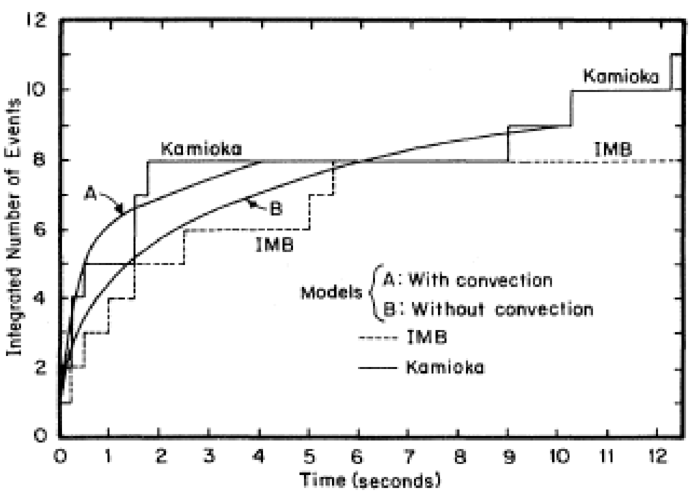
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Testing the model: SN1987A

Unique opportunity to test the core-collapse neutrino generating theory was the supernova of February 1987 in the Large Magellanic Cloud.

Expected neutrino flux for the SN at this distance (about 50 kpc) was 10^{13} m^{-2}. How many detected ?

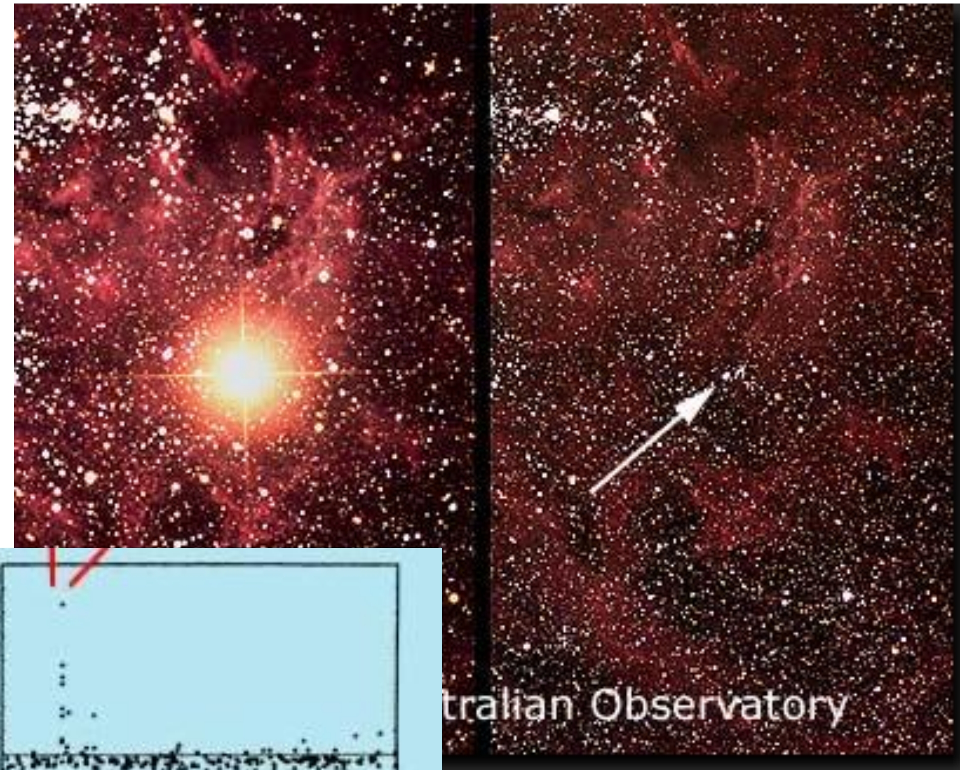
Two experiments (Kamiokande and IMB) simultaneously detected neutrino burst, and the entire neutrino capture events last 12s. This occurred *before* the SN was optically detected (or could have become visible). Time for shock wave to reach stellar surface (~1 hour).

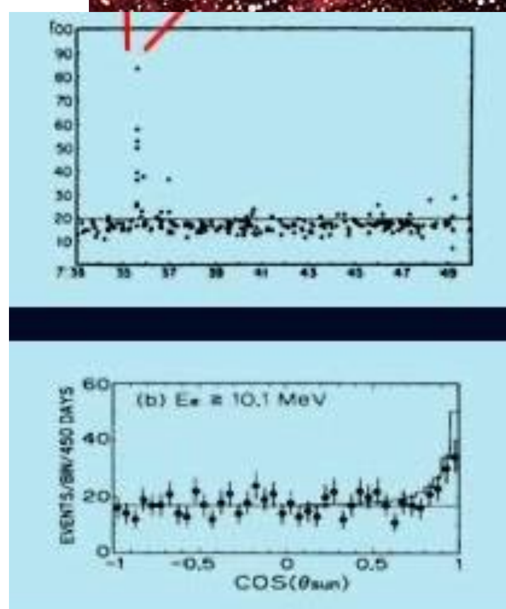


SN1987A - confirmation of core collapse

Core-collapse of massive star

- Catalogued star SK-69 202
- M=17M$_{\odot}$
- T_{eff}=17000
- Log L/ L$_{\odot}$ = 5.0
- Star has disappeared
- Neutrinos confirm neutron star formation
- No pulsar or neutron star yet seen





Nucleosynthesis in supernovae

Shock wave moves through layers of Si and the lighter elements increasing temperature to T~5×10^9 K. This has following implications:

- Nuclear statistical equilibrium reached on timescale of seconds
- As with slow core nuclear burning the products are Fe-group elements
- But main product is ^{56}Ni rather than Fe
- Timescale too short for β -decays to occur to change ratio of p/n
- Fuel (e.g. ^{28}Si) has Z/A=1/2 → product must have Z/A=1/2
- ^{56}Ni has Z/A=1/2 but ^{56}Fe=26/56<1/2
- As shock wave moves out, and T < ~2×10^9 K (around ONe layer) explosive nuclear synthesis stops
- Elements heavier than Mg produced during explosion. Lighter elements produced during preceding stellar evolution

After the "photospheric" stage, the luminosity is powered by the decay of radioactive ^{56}Ni

β -decays release energy:

3×10^{12} JKg^{-1} for ^{56}Ni

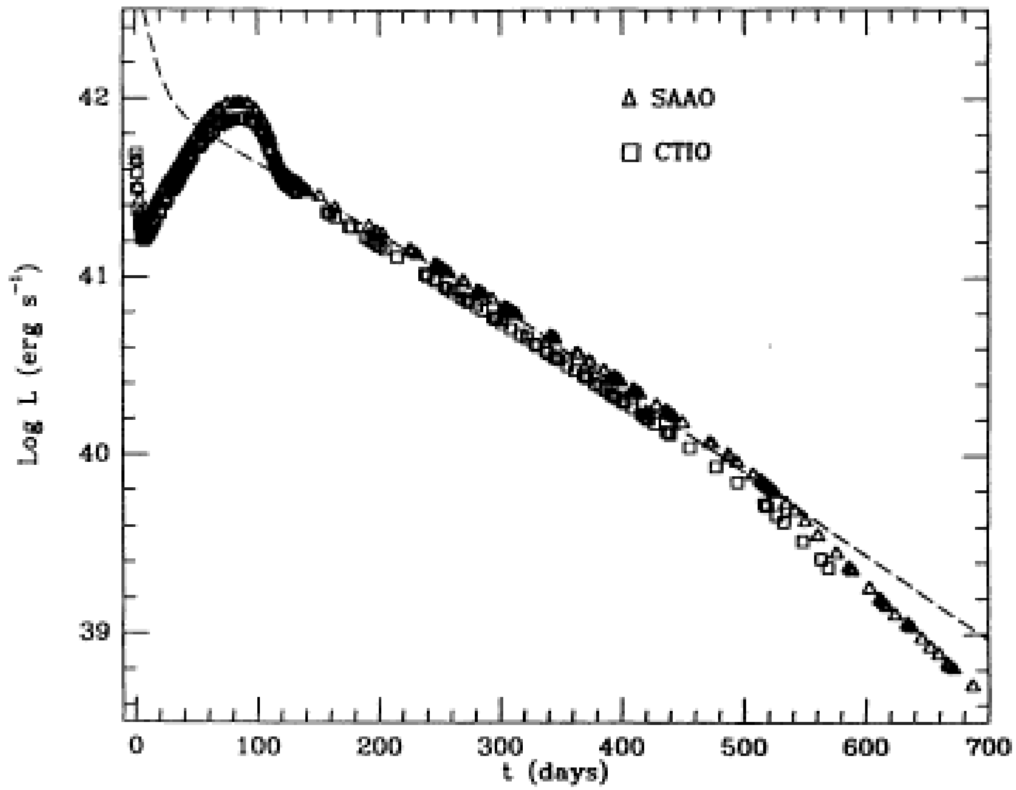
6.4×10^{12} JKg^{-1} for ^{56}Co

γ -ray lines (1.24Mev from ^{56}Co decay) detected by space and balloon experiments between 200-850 days.

Rate of lightcurve decline gives excellent match to the radioactive energy source half-life.

If distance is known, the mass of ^{56}Ni can be determined. For SN1987A:

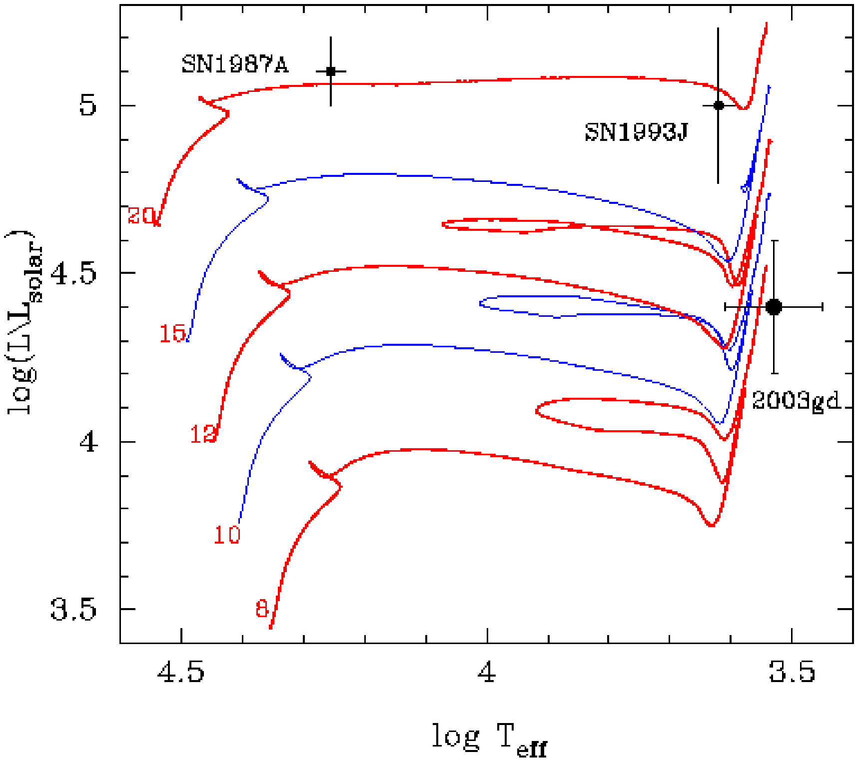
$M(^{56}Ni) = 0.075 M_\odot$



$$^{56}Ni \rightarrow {}^{56}Co + e^+ + \nu_e + \gamma \quad (\tau_{1/2} = 6 \text{ days})$$

$$^{56}Co \rightarrow {}^{56}Fe + e^+ + \nu_e + \gamma \quad (\tau_{1/2} = 77.1 \text{ days})$$

Red supergiant progenitor - SN2003gd



SN1987A progenitor was a blue supergiant. Progenitor detection difficult. Only one example of a red supergiant of a normal Type II supernova

Summary

- Stars or more than 8-10$M_\odot$ will fuse elements to create Fe core
- Core collapses and neutron star formed
- Bounce of nuclear density neutron star initiates outward shock
- Shock must have further energy input
- Likely this comes from neutrinos
- Neutrino emission accounts for 99% of the gravitational potential energy of collapsing core
- Explosions are likely neutrino driven
- Typical Type II SN have plateau phase as shock wave moves through star
- Then enter "tail-phase", luminosity source iu radioactive ^{56}Ni created explosively in SN
- Two massive stars directly confirmed coincidence with SN
- Neutrinos and γ-ray lines detected directly