Supernova events and neutron stars

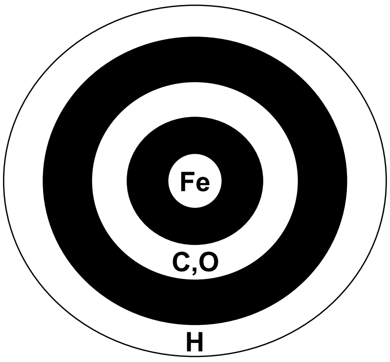
- So far, we have followed stellar evolution up to the formation of a C-rich core.
- For massive stars ($M_{initial} > 8\ M_{Sun}$), the contracting He core proceeds smoothly to C-fusion for $T_c \sim 10^9$ K

Reactions include:

$$C + He \rightarrow O\ ;$$
$$C + C \rightarrow Ne + He\ ;$$
$$2Ne \rightarrow O + Mg$$

^{24}Mg can capture α - particles to produce ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca........^{56}Fe.

- Iron group elements around ^{56}Fe most stable (even - even nuclei).
- Further reactions require input energy (endergonic) → end of normal progression of nuclear fusion.



Fusion in massive stars → strongly differentiated structure (onion-skin model)

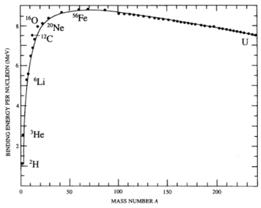


Fig. 1.3 Binding energy per nucleon for atomic nuclei. There is a broad maximum at mass number 56 which implies that energy is normally released when two light nuclei fuse to form a heavier nucleus provided the nucleus formed has a mass number less than 56.

- Fe core: $\rho \sim 10^{11}$ kgm^{-3} ; $T_c \sim 4 \times 10^9$ K
- Durations of various fusion stages for star $\sim 25\ M_{Sun}$:

H:	7×10^6 yr
He:	5×10^5 yr
C:	600 yr
Ne:	1 yr
O:	1 / 2 yr
Si:	1 day

- When $T_c > 5 \times 10^{10}$ K, kinetic energy of particles large enough to cause dissociation.

$$^{56}Fe \rightarrow 13\ ^{4}He + 4n$$
$$^{4}He \rightarrow 2p + 2n$$

- Hence k.e. ↓ , pressure ↓

  → rapid collapse of central regions on the free-fall time scale ≤ 1000 seconds

  → T ↑ even more and density ↑ to nuclear values $\sim 10^{17}$ kgm^{-3} and so

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

- Neutron star formed:

- core ~ 15 km radius,
- composed of degenerate neutron gas
- supported by neutron-degeneracy pressure
- Theoretical masses > 1.4 M_{Sun} up to ~ 3 - 4 M_{sun}

Observational determinations of masses of neutron stars from high-mass and low-mass X-ray binaries all cluster around 1.4 Msun

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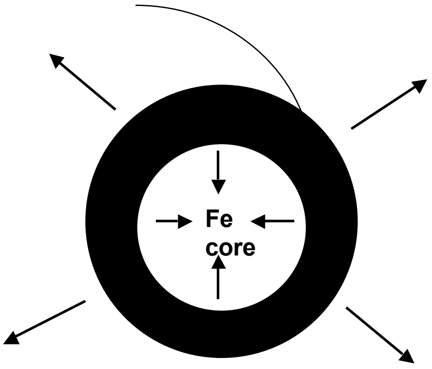
- Envelope caves in too - heats up rapidly, bounces off nuclear density core causing rapid nuclear fusion on 1 - sec time scales.



- Shock wave travels out through star and blows star apart ie A SUPERNOVA EVENT.

SN 1987A in the LMC

What was observed:

- **Within several seconds of core collapse ν and $\bar{\nu}$ escape from the core**
- **detected by two experiments**
  - **Japan: 11 events; 7.5 - 36 MeV**
  - **USA: 8 events; 20 - 40 MeV**

such energies correspond to $T \sim 10^{10}$ K

ν detectors - large tanks of highly-purified water - surrounded by 100s of photomultipliers.

Important reaction

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

If the positron recoils with a velocity > phase velocity of light in water, it emits CERENKOV radiation- flashes of blue light recorded by the photomultipliers.

- Seen in optical when shock wave reaches surface of star - very sudden rise in brightness.
- Surface T falls rapidly over few days to T ~ 5500K but radius of star increases monotonically - hence steady increase in bolometric luminosity.
- Note also decrease in expansion velocity during this time

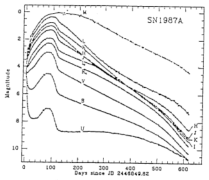


Figure 3. Light curves for SN1987A.

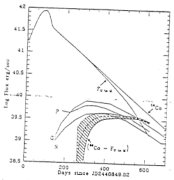


Figure 7. Comparison between flux expected from decay of 0.078 $M_\odot$ of ^{56}Co (straight line) and U to M bolometric flux curve for SN1987A (contiguous line). In constructing the observed flux curve, we have obtained M values where necessary from the smoothed K light curve and ($K-M$) colour curve. The dashed line represents the difference (^{56}Co decay − bolometric flux) and the hatched area shows the effect of an uncertainty of ±0.02 mag in fitting the observed to the expected curve. The lower three continuous lines show the predictions of models for the X- and γ-ray flux, as described in the text (P = Pinto *et al.* 1988; G = Grebenev & Sunyaev 1988; N = Nomoto *et al.* 1988).

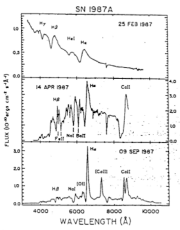


Figure 2 The optical spectrum of SN 1987A at three different epochs: (*a*) February 25, 1987, only 40 hr after core collapse. Note the broad profiles of the hydrogen and helium lines and the large blueshifts of the P Cygni absorption components. (*b*) April 14, 1987, 50 days after core collapse. The spectrum is now dominated by lines of low ionization elements. Note the strength of the barium line at 6142 Å. (*c*) September 9, 1987, more than 100 days after the maximum of the bolometric light curve. The spectrum has by this time taken on more of a nebular appearance, with strong emission lines of hydrogen, oxygen, calcium, and sodium dominating [observations from Cerro Tololo Inter-American Observatory; figure from (359)].

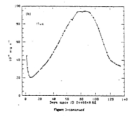
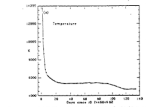


Figure 3—continued



re 3. Derived quantities for SN 1987a from blackbody fitting plotted as a function of time assuming A_V=0.6. The perature is shown in (a). The flux, assuming a distance modulus of 18.5, is shown in (b). Note how the change in rate of decline at about day 120 may indicate that SN 1987a is now showing radioactive decline.

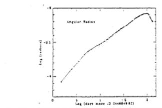


Figure 4. The radius of the photosphere in radians, derived from blackbody fitting to the photometry and assuming A_V=0.6, is shown as a function of time.

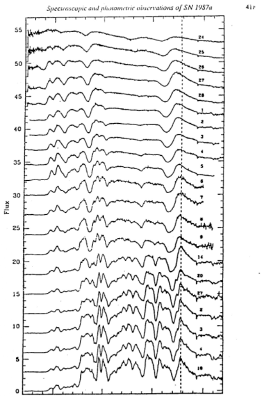


Figure 1. Flux calibrated spectra of SN 1987a. The date of observation is given above the atmospheric '*b*'-band in each spectrum. The unit on the vertical scale is 10^{-11} erg cm^{-2} s^{-1} Å^{-1}. For clarity of display the zero point of each spectrum is shifted vertically with respect to the one below it. The bottom 11 spectra are separated by 3 units from one another while the remainder are shifted by 2.3 units each. The dotted line shows the rest wavelength of Hα.

- **'plateau'** phase of light curve - passage of shock front produces lots of Ni which undergoes radioactive decay:

$$^{56}_{28}\mathrm{Ni} \rightarrow {}^{56}_{27}\mathrm{Co} + e^{+} + \nu_{e} + \gamma \qquad \text{then}$$

$$^{56}_{27}\mathrm{Co} \rightarrow {}^{56}_{26}\mathrm{Fe} + e^{+} + \nu_{e} + \gamma$$

with half-lives of 6 and 77 days respectively

•explains exponential decrease (linear in magnitudes)

There are two types of supernovae recognised from discoveries in other galaxies

Type I

no H lines, max abs. mag. ~ -19

Type II

H lines, max abs. mag. ~ -17

Type Ia

no He

Type Ib

He

- **Type II**:

  gravitational collapse of core of massive star + explosive nuclear fusion → neutron star core remnant + most of star ejected into ISM.

- **Type Ib**:

  massive star in close binary system which has lost most of H envelope during mass transfer to companion. Hence SN event (Type II) with no H lines seen.

- **Type Ia**:

  white dwarf in binary, with Roche-lobe filling companion transferring matter to white dwarf. As WD mass → 1.4 M_{Sun} onset of carbon burning in centre - carbon burning front moves out - nuclear runaway disrupts entire star.

Chemical enrichment of ISM

- **Mass - loss episodes for stars:**

m-s: stellar winds - unprocessed H + He + Z

r-g: again unprocessed gases / dust

AGB: He - shell flash episodes eject envelope material and cause convection (mixing) of gases into core e.g.

$$^{12}\mathrm{C} + {}^{1}\mathrm{H} \rightarrow {}^{13}\mathrm{C}\,;$$

$$^{13}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \mathrm{n}$$

- Before n can be captured, β - decay

$$n \rightarrow p + \mathrm{e}^{-} + \overline{\nu}$$

and protons (p) build heavier nuclei in mass-number range 24-50.

→ proton-rich material, called s - process elements (slow process, since β - decay has time to happen).

An H-deficient flow in A58 35P

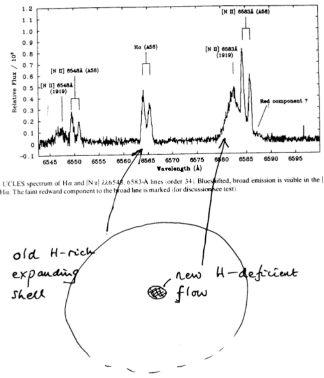


Figure 2. UCLES spectrum of Hα and [N II] λλ6548, 6583-Å lines (order 34). Blueshifted, broad emission is visible in the [N II] lines but is absent in Hα. The faint redward component to the broad line is marked (for discussion see text).

- **Type II SN events**

  large flux of neutrons produced during explosive event; captured before they β - decay to protons - hence neutron rich material, called r - process elements (rapid process) up to heavy radioactive elements like ^{238}U