PH20016 : Particles, Nuclei and Stars

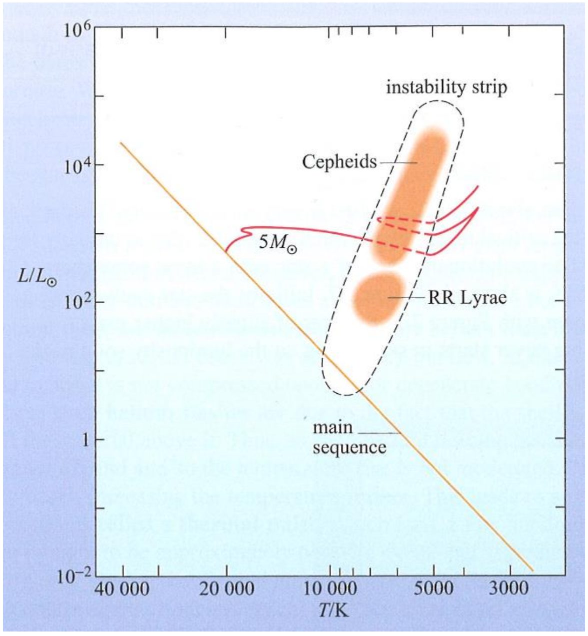
Lecture 4 Neutron-Capture Nucleosynthesis — Dr S R Davies

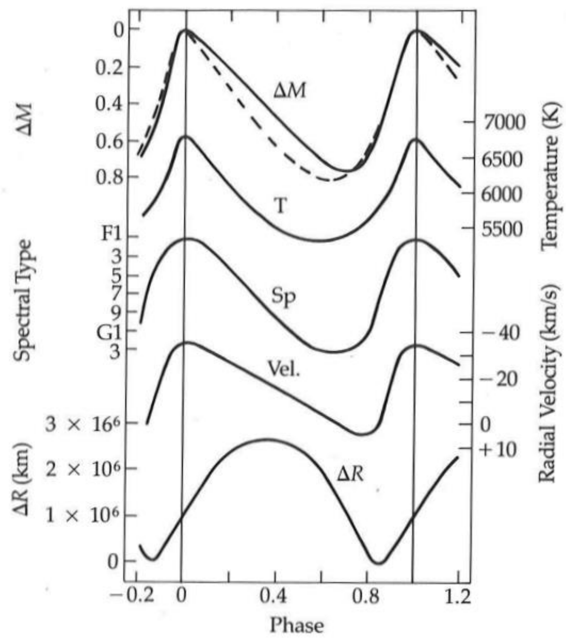
Variable Stars

Characteristic periods of the main types of pulsating stars are summarised below.

Type	M_V	Period	Cause
Cepheid	0 to –6	5 to 10 days	Pop I stars undergoing thermal pulsations
RR Lyrae	0 to –3	0.1 to 1 day	Pop II stars, 0.5 $M_\odot$, during core He burning
Semiregular red	–1 to –3	100–200 days	Cool red giants ejecting gas and dust; irregular

Population II stars: very old stars with a low abundance of "metals"
Population I stars: younger stars with a higher abundance of "metals", such as the Sun.





Cepheid Variables

- Pop I star, at top of giant branch of H-R
- mass ~ 3-18 $M_\odot$, M_V ~ 0 to –6, P ~ 5 to 10 days
- Pulsations in radius, magnitude, surface temp. very regular

Changes in the opacity of the outer layers of the star control the energy transport.

- low opacity → radiation flows freely → star bright
- high opacity → radiation absorbed → star fainter

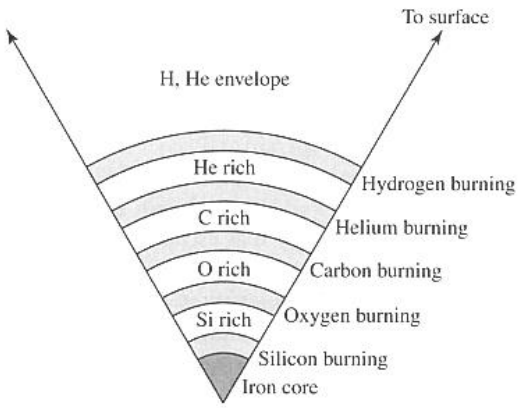
The outer layers of pulsating stars have a region of ionised He, the opacity of which increases as it absorbs UV photons to become doubly ionised.

Cepheid variables show a very strong correlation between the variation period and the mean luminosity of the star. They provide an essential tool for establishing cosmic distances.

In visual band: $M_V = -2.8 \log_{10} P_d - 1.43$ (P_d = period in days)

In terms of average luminosity $\log_{10} \frac{\langle L \rangle}{L_\odot} = 1.15 \log_{10} P_d + 2.47$

Supernovae



In general, the material in the central regions of a star is not well-mixed.

Elements are formed in shells, following the temperature gradient through the star. The heaviest elements will form at the centre (up to iron for stars > 12 $M_\odot$)

In massive stars with an iron core, silicon burning can add iron to the core until

→ core mass exceeds Chandrasekhar limit $\sim 1.4 M_\odot$

→ deg. electron gas pressure cannot withstand grav. collapse

Two processes occur :

- At ~ 6 x 10^9 K, ***photodisintegration*** of iron occurs

  $^{56}\text{Fe} + \gamma \rightarrow 13\,^{4}\text{He} + 4n$ ***endothermic*** … absorbs ~ 100 MeV

- Electron capture

  $^{4}\text{He} \rightarrow 2p + 2n$

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

- core robbed of energy → dramatic collapse
- core collapses in ~ 1 second
- core turned into degenerate neutron gas

Outlying material falls onto neutron core

→ Energetic rebound

→ Shock wave driven through star, causing heating

→ Huge onset of fusion reactions throughout star

→ Star blows itself apart

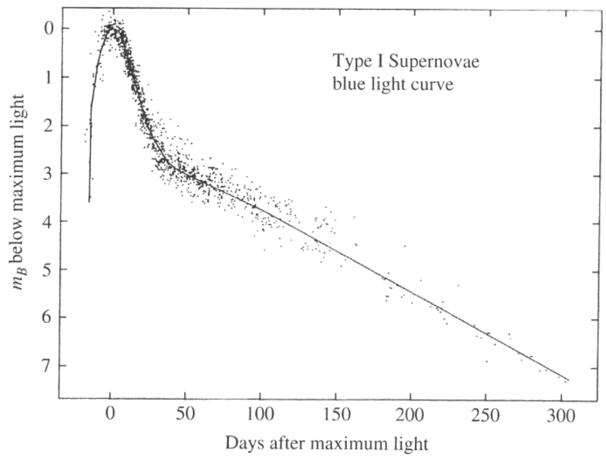
Star briefly increases in optical luminosity by ~ x 10^8 (time scale ~ few days)

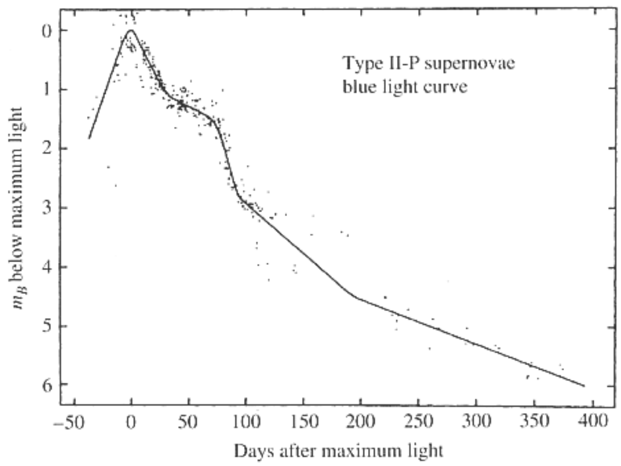
> 99% of energy carried away by neutrinos

Collapsed core remains as a ***neutron star*** dia. ~ 10 km; density ~ 10^{17} kg.m^{-3}

or a ***black hole***

Two main types of supernovae occur, distinguished by their spectra and their light curves:





Detailed study of their spectra suggest that

- Type I supernovae result from evolved stars of low and intermediate mass

- Type II result from more massive stars.

Type II supernovae:

- see strong emission of H_α lines
- " large flux of neutrinos
- occur in cores of red supergiants (> 10 $M_\odot$)
- leaves behind a neutron star or black hole

Type I supernovae are subdivided into 3 categories. We will just consider Type Ia supernovae

- see strong Si II lines; no strong H or He lines

Modelling suggests these supernovae:

- occur in binary systems: red giant + white dwarf
- matter spirals onto W.D. → mass rises
  → core mass exceeds $M_{Ch} \sim 1.4 M_\odot$
- rapid onset of C and O fusion (creates Si)

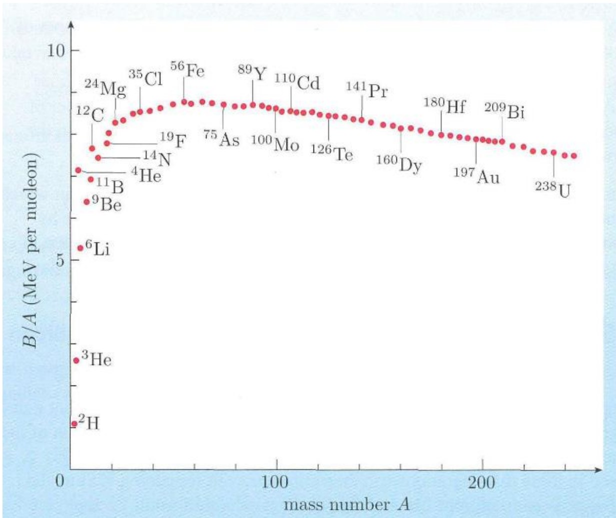
Type Ia supernovae typically have $M_V \approx -19$, with little variation

… used as a ***standard candle*** … can establish distances to ***very distant galaxies***.

Nucleosynthesis of High-Z Nuclei

We have discussed how fusion between nuclei is inhibited by the Coulomb barrier between the positively charged nuclei. There are, of course, series of reactions for which there is no Coulomb barrier: neutron-capture by nuclei.

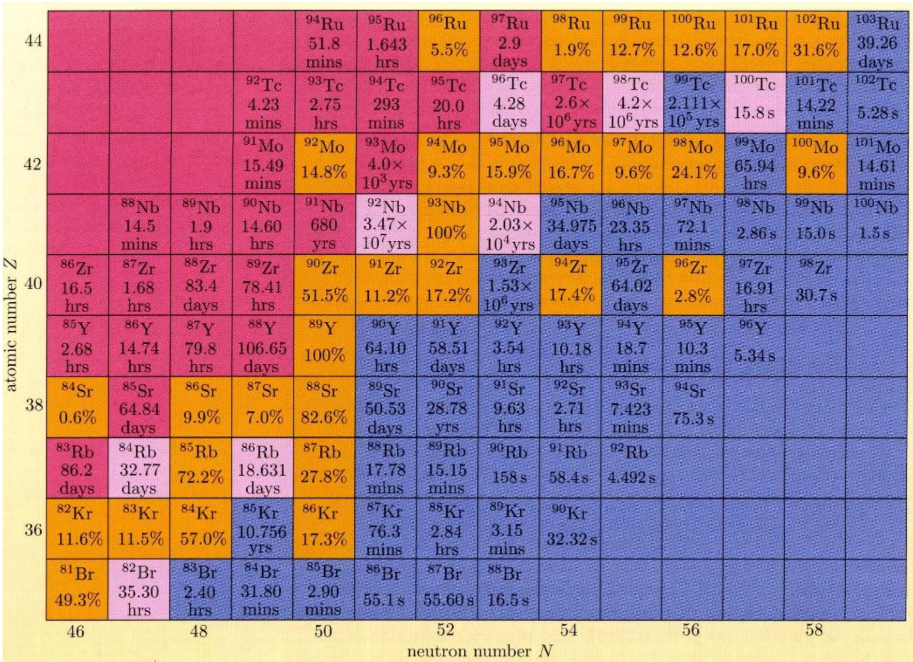
This is particularly important for creation of nuclei with masses higher than the broad peak near iron in the plot of binding energy per nucleon.



Although certain fusion reactions within the cores of massive stars may momentarily result in higher-mass nuclei, they would tend to break up into smaller nuclei through photodisintegration.

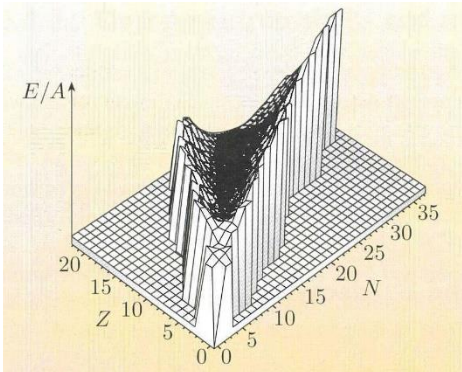
Neutron-capture reactions are the main mechanism for nucleosynthesis of higher mass nuclei (and for some light nuclei).

Nucleosynthesis pathways can be visualised using the ***chart of nuclides***, a small region of which is shown below. Isotopes of a given element are seen in horizontal rows. Those marked in orange(!) are stable (percentage of the element in this isotope indicated). For unstable isotopes, the half-life is given. Nuclei marked in blue can transform into stable nuclei through beta-decay; those marked in dark pink through electron capture (light pink is electron capture or beta decay). Stable nuclei occupy a roughly diagonal zone called the ***valley of stability***, clearly seen in a 3-D plot of total energy per nucleon plotted against both Z and N.



atomic number Z	46		48		50		52		54		56		58	
44					^{94}Ru 51.8 mins	^{95}Ru 1.643 hrs	^{96}Ru 5.5%	^{97}Ru 2.9 days	^{98}Ru 1.9%	^{99}Ru 12.7%	^{100}Ru 12.6%	^{101}Ru 17.0%	^{102}Ru 31.6%	^{103}Ru 39.26 days
				^{92}Tc 4.23 mins	^{93}Tc 2.75 hrs	^{94}Tc 293 mins	^{95}Tc 20.0 hrs	^{96}Tc 4.28 days	^{97}Tc 2.6×10^{6} yrs	^{98}Tc 4.2×10^{6} yrs	^{99}Tc 2.111×10^{5} yrs	^{100}Tc 15.8 s	^{101}Tc 14.22 mins	^{102}Tc 5.28 s
42				^{91}Mo 15.49 mins	^{92}Mo 14.8%	^{93}Mo 4.0×10^{3} yrs	^{94}Mo 9.3%	^{95}Mo 15.9%	^{96}Mo 16.7%	^{97}Mo 9.6%	^{98}Mo 24.1%	^{99}Mo 65.94 hrs	^{100}Mo 9.6%	^{101}Mo 14.61 mins
		^{88}Nb 14.5 mins	^{89}Nb 1.9 hrs	^{90}Nb 14.60 hrs	^{91}Nb 680 yrs	^{92}Nb 3.47×10^{7} yrs	^{93}Nb 100%	^{94}Nb 2.03×10^{4} yrs	^{95}Nb 34.975 days	^{96}Nb 23.35 hrs	^{97}Nb 72.1 mins	^{98}Nb 2.86 s	^{99}Nb 15.0 s	^{100}Nb 1.5 s
40	^{86}Zr 16.5 hrs	^{87}Zr 1.68 hrs	^{88}Zr 83.4 days	^{89}Zr 78.41 hrs	^{90}Zr 51.5%	^{91}Zr 11.2%	^{92}Zr 17.2%	^{93}Zr 1.53×10^{6} yrs	^{94}Zr 17.4%	^{95}Zr 64.02 days	^{96}Zr 2.8%	^{97}Zr 16.91 hrs	^{98}Zr 30.7 s	
	^{85}Y 2.68 hrs	^{86}Y 14.74 hrs	^{87}Y 79.8 hrs	^{88}Y 106.65 days	^{89}Y 100%	^{90}Y 64.10 hrs	^{91}Y 58.51 days	^{92}Y 3.54 hrs	^{93}Y 10.18 hrs	^{94}Y 18.7 mins	^{95}Y 10.3 mins	^{96}Y 5.34 s		
38	^{84}Sr 0.6%	^{85}Sr 64.84 days	^{86}Sr 9.9%	^{87}Sr 7.0%	^{88}Sr 82.6%	^{89}Sr 50.53 days	^{90}Sr 28.78 yrs	^{91}Sr 9.63 hrs	^{92}Sr 2.71 hrs	^{93}Sr 7.423 mins	^{94}Sr 75.3 s			
	^{83}Rb 86.2 days	^{84}Rb 32.77 days	^{85}Rb 72.2%	^{86}Rb 18.631 days	^{87}Rb 27.8%	^{88}Rb 17.78 mins	^{89}Rb 15.15 mins	^{90}Rb 158 s	^{91}Rb 58.4 s	^{92}Rb 4.492 s				
36	^{82}Kr 11.6%	^{83}Kr 11.5%	^{84}Kr 57.0%	^{85}Kr 10.756 yrs	^{86}Kr 17.3%	^{87}Kr 76.3 mins	^{88}Kr 2.84 hrs	^{89}Kr 3.15 mins	^{90}Kr 32.32 s					
	^{81}Br 49.3%	^{82}Br 35.30 hrs	^{83}Br 2.40 hrs	^{84}Br 31.80 mins	^{85}Br 2.90 mins	^{86}Br 55.1 s	^{87}Br 55.60 s	^{88}Br 16.5 s						

neutron number N



Certain nuclei are very stable … those for which N and/or Z correspond to ***magic numbers***, which have values 2, 8, 20, 50, 82, 126. These are interpreted in terms of ***closed shells*** … analogous to full electron shells at $Z = 2$, 10, 18, etc. Nuclei with closed neutron shells, e.g. at $N = 50$, have low neutron-capture cross-sections and correspondingly high probability of remaining in that state.

There are two main regimes of neutron-capture nucleosynthesis:

If neutrons captured ***slowly*** w.r.t. beta-decay ($n \rightarrow p + e^{-} + \bar{\nu}_e$)

→ ***s-process*** (slow) → proton-rich elements

Occurs during core-He fusion in massive stars and during ***thermal pulsation in red giants*** (the TP-AGB phase mentioned in Lecture 3).

The main stellar fusion reactions that create the neutrons are:

$$^{13}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + n$$
$$^{22}\mathrm{Ne} + {}^{4}\mathrm{He} \rightarrow {}^{25}\mathrm{Mg} + n$$

If neutrons captured ***rapidly*** w.r.t. beta-decay

→ ***r-process*** (rapid) → neutron-rich elements

Occurs during ***core-collapse SN*** and ***neutron star collisions***.

In general, the s-process pathway will remain close to the valley of stability.

The s-process produces many nuclei with closed neutron shells, corresponding to peaks in abundance around $A \approx 90$, 138, etc.

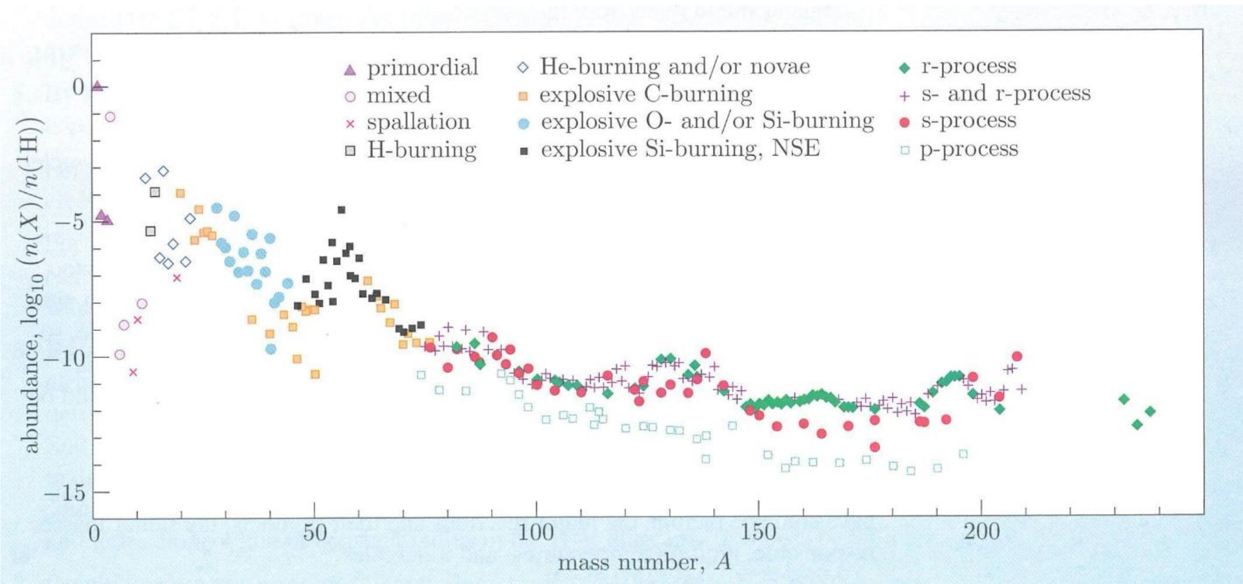
^{89}Nb 1.9 hrs	^{90}Nb 14.60 hrs	^{91}Nb 680 yrs	^{92}Nb 3.47×10^{7}yrs	^{93}Nb 100%	^{94}Nb 2.03×10^{4}yrs	^{95}Nb 34.975 days	^{96}Nb 23.35 hrs	^{97}Nb 72.1 mins
^{88}Zr 83.4 days	^{89}Zr 78.41 hrs	^{90}Zr 51.5%	^{91}Zr 11.2%	^{92}Zr 17.2%	^{93}Zr 1.53×10^{6}yrs	^{94}Zr 17.4%	^{95}Zr 64.02 days	^{96}Zr 2.8%
^{87}Y 79.8 hrs	^{88}Y 106.65 days	^{89}Y 100%	^{90}Y 64.10 hrs	^{91}Y 58.51 days	^{92}Y 3.54 hrs	^{93}Y 10.18 hrs	^{94}Y 18.7 mins	^{95}Y 10.3 mins
^{86}Sr 9.9%	^{87}Sr 7.0%	^{88}Sr 82.6%	^{89}Sr 50.53 days	^{90}Sr 28.78 yrs	^{91}Sr 9.63 hrs	^{92}Sr 2.71 hrs	^{93}Sr 7.423 mins	^{94}Sr 75.3 s
^{85}Rb 72.2%	^{86}Rb 18.631 days	^{87}Rb 27.8%	^{88}Rb 17.78 mins	^{89}Rb 15.15 mins	^{90}Rb 158 s	^{91}Rb 58.4 s	^{92}Rb 4.492 s	
^{84}Kr 57.0%	^{85}Kr 10.756 yrs	^{86}Kr 17.3%	^{87}Kr 76.3 mins	^{88}Kr 2.84 hrs	^{89}Kr 3.15 mins	^{90}Kr 32.32 s		
^{83}Br 2.40 hrs	^{84}Br 31.80 mins	^{85}Br 2.90 mins	^{86}Br 55.1 s	^{87}Br 55.60 s	^{88}Br 16.5 s			

Many nuclear species have contributions from both r and s-processes.

Some species are formed (almost) ***only by the r-process***
(e.g. if immediately right of an unstable isotope). Example: ^{91}Rb

Some species are formed (almost) ***only by the s-process***
(e.g. if shielded by a stable nucleus below and right of it). Example: ^{86}Sr and ^{87}Sr

The figure below shows abundances (logarithmic, normalised relative to hydrogen) for stable isotopes. This plot shows the nuclei created through fusion reactions in low and high mass stars and the neutron-capture elements to the right of the iron peak.



Nuclei lying on the proton-rich side of the valley of stability can be formed through photodisintegration and via a variety of proton-capture reactions, such as the rp-process and the p-process, which will not be discussed here. Proton-capture involves high Coulomb barriers, making it much less probable than neutron-capture. It also requires an environment combining very high temperatures with an abundance of hydrogen. (One possible scenario would be an accreting binary system, where one star is a neutron star.)