From nuclei to stars

Nucleosynthesis processes in the Universe: from Big-Bang to stars

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Outline

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Lecture 2: Nucleosynthesis processes in the Universe

1. A little bit of history
2. Big-Bang nucleosynthesis
3. Cosmic ray nucleosynthesis
4. Stellar nucleosynthesis
   • Hydrogen burning: p-p chains and CNO cycles
   • Helium burning
   • Advanced burning stages: C, Ne, O and Si burning
   • Explosive nucleosynthesis
   • Nucleosynthesis beyond iron: s- and r-process
5. Back to the Hertzsprung-Russel diagram

Lecture 3: Cross-sections and thermonuclear reaction rates

Lecture 4: Experimental approaches in nuclear astrophysics
1. A little bit of history

When and where?
Important dates

- 1920 – Aston: mass of the helium atom is slightly less than four times the mass of the hydrogen
- 1928 – Eddington: suggests that Aston’s discovery would explain the energy generation in Sun
- 1928 – Gamow, Condon & Gourney: 1st calculation of the quantum tunneling probability
- 1929 – Atkinson & Houtermans: suggest that Gamow’s results may explain energy generation

- 1932 – Cockcroft & Walton: 1st induced nuclear reaction $^7\text{Li}(p,\alpha)\alpha \rightarrow \text{pp chain}$
- 1934 – Lauritsen & Crane: 10 min radioactivity produced $^{12}\text{C}(p,\gamma)^{13}\text{N} \rightarrow \text{CNO cycle}$

- 1936 – Atkinson, Bethe & Critchfield: p+p reactions give correct energy generation in Sun
- 1936 – von Weizsaker & Bethe: energy generation in stars produced via the CNO cycle

- 1957 – Burbridge, Burbridge, Fowler & Hoyle \textbf{Overview of nucleosynthesis processes}
- 1957 – Cameron

- 1968 – 1st detection of neutrinos emitted by the Sun core
- 1969 – 1st detection of $^{26}\text{Al}$ $\gamma$-ray decay in the Milky Way
- 1987 – $\gamma$-ray detection of $^{56}\text{Co}$ and $^{57}\text{Co}$ decays in supernova SN 1987A
- 2013 – observational evidences of heavy nuclei nucleosynthesis in the coalescence of a binary system of two neutron stars (GRB 130603B)
- 2017 – Observational confirmation of heavy nuclei nucleosynthesis in a binary neutron star merger (GW 170817)
Two views….

Primordial nucleosynthesis

« All the elements were formed just after Big-Bang »
Phys. Rev. 73. (1948) 803

Almost true for D, He and a part of $^7$Li
BUT no stable isotopes with $A = 5$ and $A = 8$ (mass gap)

Stellar nucleosynthesis

« All elements are synthesized in stars through various processes »
Rev. Mod. Phys. 29 (1957) 547

History
Identified nucleosynthesis processes

- Primordial (Big-Bang) nucleosynthesis
- Hydrogen and Helium burning
- “e” process (iron peak)
- “x” process (LiBeB; “x” for unknown)
- “r” process (rapid neutron capture)
- “s” process (slow neutron capture)
- “p” process (proton rich)

Today

- “x” is identified as non-thermal nucleosynthesis (cosmic rays)
- Additional burning stages identified: C, Ne, O, Si
2. Big Bang nucleosynthesis

- $10^{-32}$ seconds: Cosmic inflation ends
- $10^{-6}$ seconds: Protons form
- 100 seconds: Deuterium, helium and lithium are synthesized
- 100 million years: First stars form
- 500 million years: Current record holder for earliest known galaxy
- 4 billion years: Star formation peaks
Observational pillars for Big-Bang model

• The expansion of the Universe
  Galaxies move away from each other and from us according to Hubble’s law: \( V = H_0 \times D \), where \( H_0 \approx 70 \text{ km/s/pc} \) is the Hubble “constant”

• The Cosmic Microwave Background radiation (CMB)
  Black body radiation at 2.7 K corresponding to the redshifted spectrum emitted when the Universe became transparent (Penzias & Wilson, 1965)

• Primordial nucleosynthesis (BBN) of light elements
  BBN reproduces the observed primordial abundances over a range of nine orders of magnitudes!
Nucleosynthesis (1)

• For $T > 10$ GK, the energy density is dominated by radiation (photons and neutrinos), and all weak, strong and electromagnetic processes established a thermal equilibrium

• $n \leftrightarrow p$ equilibrium driven by weak interactions:
  \[(1): \nu_e + n \leftrightarrow e^- + p \quad (2): \bar{\nu}_e + p \leftrightarrow e^+ + n \quad (3): n \leftrightarrow p + e^- + \bar{\nu}_e\]

\[
\frac{N_n}{N_p} = e^{-Q_{np}/kT} \quad Q_{np} = 1.29\,\text{MeV}
\]

• Equilibrium as long as the weak reaction rate \([(1) + (2)]\) are faster than the expansion rate, hence breaks out when:

\[
\Gamma_{n\leftrightarrow p} \sim H(t)
\]

• Decoupling and freezeout $t \approx 10$ s after Big-Bang when $T \approx 3$ GK and $N_n/N_p \approx 1/6$
Nucleosynthesis (2)

- After freezeout the dominant weak interaction is the decay of free neutrons to protons
  \[ n \rightarrow p + e^- + \bar{\nu}_e \]

- Neutrons decay until \( T \) is low enough so that:
  \[ n + p \rightarrow D + \gamma \]

  becomes faster than deuterium photodisintegration
  \[ \gamma + D \rightarrow n + p \]

- This occurs at \( t \approx 200 \text{ s} \) (3 min) when \( T \approx 0.9 \text{ GK} \) and \( N_n/N_p \approx 1/7 \)

- Nucleosynthesis starts to produce essentially \( ^4\text{He} \) together with traces of \( ^3\text{He}, ^7\text{Li}, \ldots \)

\[ N_n/N_p \approx 1/7 = 2/14 \quad \rightarrow \quad X(^4\text{He}) \approx 4 / (4 + 12) \approx 0.25 \]
The canonical BBN reaction network

- Standard BBN: no convection, no mixing, no diffusion, known physics
- The 12 reactions of standard BBN:

  \[
  \begin{align*}
  \bullet & \quad n \leftrightarrow p \quad \text{and} \quad \tau_n = 880 (4) \text{ s} \\
  \bullet & \quad p + n \rightarrow D + \gamma \\
  \bullet & \quad D + p \rightarrow ^3\text{He} + \gamma \\
  \bullet & \quad D + D \rightarrow ^3\text{He} + n \\
  \bullet & \quad D + D \rightarrow T + p \\
  \bullet & \quad T + D \rightarrow ^4\text{He} + n \\
  \bullet & \quad T + ^4\text{He} \rightarrow ^7\text{Li} + \gamma \\
  \bullet & \quad ^3\text{He} + n \rightarrow p + T \\
  \bullet & \quad ^3\text{He} + D \rightarrow p + ^4\text{He} \\
  \bullet & \quad ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \\
  \bullet & \quad ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He} \\
  \bullet & \quad ^7\text{Be} + n \rightarrow ^7\text{Li} + p
  \end{align*}
  \]

Number of baryons per photon: \( \eta \equiv n_b / n_\gamma \)

Baryonic density of the Universe: \( \Omega_b h^2 = 3.65 \times 10^7 \eta \)
Predictions vs observations

Observations from a set of primitive objects when the Universe was young

- **D observations**: in remote cosmological clouds (i.e. at high redshift) on the line of sight of quasars
  \[ \text{D}/\text{H} = (2.527 \pm 0.030) \times 10^{-5} \]

- **\(^4\)He observations**: in H II (ionized H) regions of blue compact galaxies
  \[ \text{\(^4\)He}/\text{H} = 0.2449 \pm 0.0040 \]

- **\(^3\)He observations**: in HII regions of our Galaxy
  \[ \text{\(^3\)He}/\text{H} = (1.1 \pm 0.2) \times 10^{-5} \]

- **\(^7\)Li observations**: at the surface of low metallicity stars in the halo of our Galaxy
  \[ \text{\(^7\)Li}/\text{H} = 1.58^{+0.35}_{-0.28} \times 10^{-10} \]
Solutions to the $^7$Li problem?

Several possibilities are considered

- Astrophysical solution
- Nuclear physics solution
- Physics beyond the standard model
Primordial $^7$Li abundance measured in old metal poor halo dwarf stars

Spite plateau (Spite & Spite, 1982)
- $\text{Li/H} \approx 1.12 \times 10^{-10}$
- Very low dispersion

Spite plateau indicates that the bulk of the lithium is unrelated to galactic nucleosynthesis processes and thus is primordial

How reliable is Li abundance determination?
→ Systematic errors in the extraction of Li abundances due to the used atmosphere models?
→ unlikely  Asplund and Lind 2010
Could atmospheric $^7$Li be depleted by rotationally induced mixing and/or diffusion?

- Lithium easily burned in stars (low binding energy) → $^7$Li(p,α)α for $T > 2.5$ MK
- Convection brings surface material to deeper layers → lithium burning

Not enough and not uniform $^7$Li destruction
- Metal poor halo stars have shallow convective zones than in solar metallicity stars
- Stars of different masses have different convective zone size → larger scatter around $^7$Li plateau should be observed
Nuclear solution to $^7$Li problem?

- $^7$Li produced by $^7$Be decay (EC) at high $\Omega_b \hbar^2$

- Main $^7$Be production mechanism: $^3\text{He}(^4\text{He},\gamma)^7\text{Be}$
  - Various measurements of the cross-section 10% uncertainty

- Main $^7$Be destruction mechanism: $^7\text{Be}(n,p)^7\text{Li}(p,\alpha)\alpha$
  - $^7\text{Be}(n,p)^7\text{Li}$ well known cross-section 1% uncertainty
  - $^7\text{Li}(p,\alpha)\alpha$ 6% uncertainty on cross-section

- Secondary destruction mechanisms $^7\text{Be}+d$, $^7\text{Be}+^3\text{He}$, $^7\text{Be}+^4\text{He}$…
  - all experimentally studied, and none can alleviate the $^7$Li problem

Nuclear physics is very unlikely to solve the $^7$Li problem

Any additional $^7$Be destruction would alleviate the $^7$Li problem
Physics beyond the standard model?

Idea: late time neutron injection

- enhance $^7\text{Be}$ destruction by $^7\text{Be}(n,p)^7\text{Li}(p,\alpha)\alpha$ reactions
- Alleviate the Li problem at the expense (harmless) Deuterium overproduction

Two examples among many….

- Decays of heavier meta-stable (100 – 1000 s) particles that inject additional neutrons (Jedamzik (2004, 2006), Kawasaki+ (2005), Ellis+ (2005))
- Existence of a mirror universe in which neutrons can oscillate to our world (Coc+ 2013) → effective late time neutron injection
Summary

- **Big-Bang Nucleosynthesis (BBN) produces**, between 3 min and 20 min, **H, D, He** and part of **Li**

- **Heavier elements nucleosynthesis is prevented** because:
  - Larger Coulomb barriers for elements with higher atomic numbers (see next Lecture)
  - Lack of isotope of mass number $A = 5$ and $A = 8$
  - Decreasing matter density as the Universe expands

Further reading…
- NPAC, cosmology course
3. Cosmic rays nucleosynthesis

Hess (center) lands after his balloon flight in 1912

Ionization as a function of altitude (Hess)
Cosmic rays properties

Composition:  H (90 %), He (9 %), C, N, O, …. e- (1 %)

Cosmic rays are not in thermodynamic equilibrium → power law spectrum

Data from Voyager 1 probe (red circles), AMS-02 experiment (blue stars) and HEAO-3-C2 (green squares)
What is the origin of LiBeB isotopes?

What are the processes producing $^6$Li, $^7$Li, $^9$Be and $^{10,11}$B?

- **Big-Bang Nucleosynthesis**
  - significant amount of $^7$Li
  - $^6$Li, $^9$Be and $^{10,11}$B abundances predicted from BBN are at least 3 orders of magnitude below the abundances measured in metal-poor stars

- **Stellar nucleosynthesis**
  - Light elements are fragile enough (relatively low binding energy per nucleon) to be destroyed in stars during quiescent burning
  - $^7$Li in classical novae (explosive), AGB (?)
  - $^7$Li, $^{11}$B by $\nu$-induced spallation reactions

- **Galactic Cosmic Rays (GCR)**
  - Similar abundances than solar system with notable exception for LiBeB!!
Spallogenic nucleosynthesis

Non thermal nucleosynthesis induced by cosmic rays

**Spallation:** “heavy” nucleus (C, N, O, …) emits lighter fragments (Li, Be, B, …) as a result of a collision with a high-energy particle (H, He)

Proton > 10 MeV/nucleon

Helium

**C, N, O, …**

LiBeB emitted at much lower energy than incident H/He

**Inverse spallation:** heavy nucleus impinges light nucleus

Proton > 10 MeV/nucleon

**C, N, O, …**

LiBeB emitted at about same energy per nucleon as incident C, N, O, …

→ must slow down to rest (small survival probability)

Cosmic rays
Spallation cross-sections

- The decreasing sequence of B, Li and Be matches the B, Li and Be GCR abundances
- $\alpha + \alpha$ reactions important for production of $^6,^7$Li isotopes
Galactic Cosmic Rays play a major role in the production of the LiBeB elements

<table>
<thead>
<tr>
<th>Element</th>
<th>BBN</th>
<th>GCR</th>
<th>v in core-collapse supernovae</th>
<th>Low-mass stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6\text{Li}$</td>
<td></td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>12 %</td>
<td>18 %</td>
<td>&lt; 20 %</td>
<td>50 – 70 %</td>
</tr>
<tr>
<td>$^9\text{Be}$</td>
<td></td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{10}\text{B}$</td>
<td></td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{11}\text{B}$</td>
<td></td>
<td>70 %</td>
<td>30 %</td>
<td></td>
</tr>
</tbody>
</table>

Further reading...
4. Stellar nucleosynthesis

Quiescent (hydrostatic) stellar burning

Sun, Solar Dynamics Observatory

Explosive stellar burning

Classical nova, Nova Cygni 1992, HST
4.1 Quiescent hydrogen burning

- Where does it take place?
  - Core of main-sequence stars (8 – 55 MK)
  - Core of the Sun (15.6 MK)
  - Burning shell in AGB stars (45 – 100 MK)

- How does it work?
  - \(4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e\) \((Q = 26.73\ \text{MeV})\)
  - Probability for the simultaneous interaction of 4 protons far too small \(\rightarrow\) reactions sequence

- Who & when?
  - Bethe & Critchfield (1938)
  - von Weizsaecker (1938)
  - Bethe (1939)

\[\text{pp chain} \quad \text{CNO cycle}\]
The proton – proton (pp) chains

\[ p + p \rightarrow d + e^+ + \nu_e \]
\[ p + d \rightarrow ^3\text{He} + \gamma \]

\[ ^3\text{He} + ^3\text{He} \rightarrow 2p + ^4\text{He} \]

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \]
\[ ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He} \]

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]
\[ ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \]
\[ ^8\text{Be}^* \rightarrow ^4\text{He} + ^4\text{He} \]

Note: neutrinos provide direct evidence that nuclear reactions occur (see later)
The pp1 chain (1)

- Succession of 3 reactions producing almost 90% of Sun’s energy

- First reaction: \( p + p \rightarrow d + e^+ + \nu \) \((Q = 1.44 \text{ MeV})\)
  - strong + weak interactions
  - cross-section is about 20 orders of magnitude smaller than for nuclear (strong) interaction!!
  - cannot be measured
  - can be calculated

- All subsequent reactions involve nuclear and electromagnetic interactions
  - much faster

- Second reaction: \( p + d \rightarrow {}^3\text{He} + \gamma \) \((Q = 5.49 \text{ MeV})\)
  - many measurements since 1962, including one at LUNA in 2002 (see lecture 4)
• Deuterium abundance in the core of the Sun
  • Temporal evolution of deuterium = production \([p(p,e^+\nu)d]\) 
    \[-\text{destruction} \,[d(p,\gamma)^3\text{He}]\]

\[
\frac{dN_d}{dt} = \frac{N_H^2}{2} \langle \sigma v \rangle_{p(p,e^+\nu)} - N_H N_d \langle \sigma v \rangle_{d(p,\gamma)}
\]

• At equilibrium:

\[
\left( \frac{N_d}{N_H} \right)_e = \frac{\langle \sigma v \rangle_{p(p,e^+\nu)}}{2 \langle \sigma v \rangle_{d(p,\gamma)}}
\]

For \(T = 15.6\) MK (Sun)

\[
\langle \sigma v \rangle_{p(p,e^+\nu)} = 1.5 \times 10^{-43} \text{cm}^3\text{s}^{-1}
\]

\[
\langle \sigma v \rangle_{d(p,\gamma)} = 2.0 \times 10^{-26} \text{cm}^3\text{s}^{-1}
\]

\[
\left( \frac{N_d}{N_H} \right)_e = 7.5 \times 10^{-18}
\]

\[
\text{Solar D/H} \approx 2 \times 10^{-5}
\]

\[\rightarrow \text{D from BBN}\]

• Lifetime of a proton and a deuterium in the core of the Sun

We consider \(\rho_c = 150\) g cm\(^{-3}\) and \(X_H \sim X_{\text{He}} \sim 0.5\) \(\rightarrow N_H = 4.5 \times 10^{25}\) cm\(^{-3}\)

\[
\tau_H = \frac{1}{N_H \langle \sigma v \rangle_{p(p,e^+\nu)}} = 4.7 \times 10^9 \text{yr}
\]

\[
\tau_d = \frac{1}{N_H \langle \sigma v \rangle_{d(p,\gamma)}} = 1.1 \text{ s}
\]
The pp1 chain (3)

Possible reactions for $^3$He burning

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Q (MeV)</th>
<th>$S(0)$ (keV b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He(d,$\gamma$)$^5$Li(p)$^4$He</td>
<td>16.39</td>
<td>~0.3</td>
</tr>
<tr>
<td>$^3$He(d,p)$^4$He</td>
<td>18.35</td>
<td>6240</td>
</tr>
<tr>
<td>$^3$He($^3$He,$\gamma$)$^6$Be(2p)$^4$He</td>
<td>11.50</td>
<td>~0.8</td>
</tr>
<tr>
<td>$^3$He($^3$He,2p)$^4$He</td>
<td>12.86</td>
<td>5320 (80)</td>
</tr>
<tr>
<td>$^3$He($^4$He,$\gamma$)$^7$Be</td>
<td>1.59</td>
<td>0.57 (4)</td>
</tr>
</tbody>
</table>

- $^3$He + p $\rightarrow$ $^4$Li $\rightarrow$ $^3$He + p  \( (\tau = 10^{-22} \text{ s}) \)
- $^3$He + d negligible given the low deuterium abundance
- $^3$He + $^3$He $\rightarrow$ 2p + $^4$He \( (Q = 12.86 \text{ MeV}) \) → Third reaction of the pp1 chain
  → has been measured in LUNA (see lecture 4)

- If N($^4$He) $>>$ N($^3$He) [factor $> 10^4$] then $^3$He($^4$He,$\gamma$)$^7$Be is activated
  → pp2 & pp3 chains
The pp2 and pp3 chains

\(^7\)Be destruction: competition between electronic capture (EC) and proton capture

**pp2 chain**
- \(p(p,e^+\nu)d\)
- \(d(p,\gamma)^3\)He
- \(^3\)He\((^4\)He,\(\gamma)^7\)Be
- \(^7\)Be\((EC,\gamma)^7\)Li
- \(^7\)Li\((p,\alpha)\alpha\)

**pp3 chain**
- \(p(p,e^+\nu)d\)
- \(d(p,\gamma)^3\)He
- \(^3\)He\((^4\)He,\(\gamma)^7\)Be
- \(^7\)Be\((p,\gamma)^8\)Be
- \(^8\)B\((\beta^+\nu)^8\)Be
- \(^8\)Be\((\alpha,\alpha\)α

- \(^7\)Be decays by EC and its lifetime depends on its charge state
- In stars, \(^7\)Be fully ionized and then capture free electrons, so \(\tau\) depends on \(n_e\) and \(T\). In the Sun’s core \(\tau_s = 1.6\ \tau_{lab} = 120\) days
- The \(^7\)Be\((p,\gamma)^8\)B reaction is faster than \(^7\)Be EC for \(T > 25\) MK \(\rightarrow\) pp3 chain
Relative contribution of the 3 pp chains

- \( T < 18 \text{ MK} \) → pp1 chain
- \( 18 \text{ MK} < T < 23 \text{ MK} \) → pp2 chain
- \( T > 23 \text{ MK} \) → pp3 chain
- Sun (\( T = 15.6 \text{ MK} \)) → pp1 (84 %) + pp2 (14 %)
The pp chains in the Sun

\[ p + p \rightarrow d + e^+ + \nu_e [0.26 \text{ MeV}] \quad \text{99.75 \%} \]

\[ p + e^- + p \rightarrow d + \nu_e [1.44 \text{ MeV}] \quad \text{0.25 \%} \]

\[ p + d \rightarrow ^3\text{He} + \gamma \]

86 \% \quad 14 \%

\[ ^3\text{He} + ^3\text{He} \rightarrow 2p + ^4\text{He} \quad \text{pp1} \]

\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \quad \text{pp2} \]

99.89 \% \quad 0.11 \% \quad \text{pp3}

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e [0.86 \text{ MeV}] \]

\[ ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He} \]

\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

\[ ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e [6.80 \text{ MeV}] \]

\[ ^8\text{Be}^* \rightarrow ^4\text{He} + ^4\text{He} \]

The effective energy given to the Sun is smaller than \( Q = 26.73 \text{ MeV} \) because of the escape of the neutrinos.

\[ Q_{eff} = Q - 2\overline{E}_\nu(p+p) = 26.20 \text{ MeV} \quad \text{pp1} \]

\[ Q_{eff} = Q - \overline{E}_\nu(p+p) - \overline{E}_\nu(7\text{Be}) = 25.61 \text{ MeV} \quad \text{pp2} \]

\[ Q_{eff} = Q - \overline{E}_\nu(p+p) - \overline{E}_\nu(8\text{B}) = 19.67 \text{ MeV} \quad \text{pp3} \]
The CNO cycle (1)

- In population I stars (second, third… generation of stars), the elements C, N and O serve as catalysts of the transformation:

\[4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e \quad (Q = 26.73 \text{ MeV})\]

- There are four sets of reactions converting H to He → 4 CNO cycles → we will focus on the CNO-1 cycle

CNO-1

\[\begin{align*}
12\text{C}(p,\gamma)^{13}\text{N} \\
13\text{N}(\beta^+\nu)^{13}\text{C} \\
13\text{C}(p,\gamma)^{14}\text{N} \\
14\text{N}(p,\gamma)^{15}\text{O} \\
15\text{O}(\beta^+\nu)^{15}\text{N} \\
15\text{N}(p,\alpha)^{12}\text{C}
\end{align*}\]

\[\begin{align*}
^1\text{H} & \rightarrow ^4\text{He} & \rightarrow ^{13}\text{N} & \rightarrow ^{13}\text{C} & \rightarrow ^{14}\text{N} & \rightarrow ^{15}\text{O} & \rightarrow ^{15}\text{N} & \rightarrow ^{12}\text{C} \\
& & & & & & & \\
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\end{align*}\]

\[T_{1/2}^{(13}\text{N}) = 9.965 \text{ min} \\
T_{1/2}^{(15}\text{O}) = 122.24 \text{ s} \\
T_{1/2}^{(17}\text{F}) = 64.49 \text{ s} \\
T_{1/2}^{(18}\text{F}) = 109.77 \text{ min} \]
The CNO cycle (2)

- The slowest reaction $^{14}\text{N}(p,\gamma)^{15}\text{O}$ of the CNO cycle fixes:
  - the energy production rate $\epsilon \propto Q_{\text{CNO}}/\tau_{\text{CNO}}$
  - the cycle duration
    - $\tau_{\text{CNO}} = \tau_p(^{12}\text{C}) + \tau_p(^{13}\text{C}) + \tau_p(^{14}\text{N}) + \tau_p(^{15}\text{N})$
      $\simeq \tau_p(^{14}\text{N})$

  - For $\rho_c = 100 \text{ g.cm}^{-3}$, $X_H = 0.5$ and $T_c = 60 \text{ MK}$
    $\rightarrow \tau(^{12}\text{C}) = 6.1 \times 10^9 \text{ yr}$, $\tau(^{13}\text{C}) = 1.1 \times 10^9 \text{ yr}$,
    $\tau(^{14}\text{N}) = 2.1 \times 10^{12} \text{ yr}$, $\tau(^{15}\text{N}) = 1.0 \times 10^8 \text{ yr}$

- The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction has been measured directly by the LUNA collaboration (see lecture 4)
  - impact on the age of Globular Clusters (turn-off age; see lecture 1)
    \cite{Imbriani+ A&A 2013}

- CNO cycle in AGB stars is the main source of $^{13}\text{C}$ and $^{14}\text{N}$ in the Universe

Hydrogen burning
The CNO cycle (3)

- CNO cycle has a steeper temperature dependence than pp chain (see lecture 3)
- pp1 chain dominates in low mass stars (~ $M_\odot$), while CNO cycles dominates for higher mass stars (few $M_\odot$)
- Above $T = 20$ MK, CNO1 faster than pp1
  \[ \epsilon \sim T^{17} \]
  \[ \epsilon \sim T^4 \]
  → change in stellar structure at $1.15 M_\odot$, e.g. different radiative / convective zones

Hydrogen burning
The solar neutrino spectrum

Solar neutrinos
The detection of solar neutrinos (1)

The pioneering experiment (1964-2001) of R. Davis (Nobel price in 2002) and J. Bahcall

- 680 tons of perchloroethylene (C\textsubscript{2}Cl\textsubscript{4}) in the Homestake gold mine (1.5 km deep)

- $\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} \ (T_{1/2} = 35 \text{ days}) + e^-$

- Production of $^\text{37}\text{Ar}$: $\sim 0.5$ atom per day

- Radiochemical separation: extraction of the $^\text{37}\text{Ar}$ nuclei every 100 days, counting (EC $\rightarrow$ Auger electrons) in a gas detector

- Result: $2.56 \pm 0.16 \text{ (stat)} \pm 0.16 \text{ (sys)} \text{ SNU} \Rightarrow 30 \% \text{ of the expected signal}$

- Solar model (Bahcall 2004): $8.5 \pm 0.18 \text{ SNU}$

1 SNU (Solar Neutrino Unit) = $10^{-36}$ capture per second and target atom
The detection of solar neutrinos (2)

- **Radiochemical experiments** with gallium: **SAGE and GALLEX**
  - Reaction: $\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} \left( T_{1/2} = 11.4 \text{ d} \right) + e^- \text{ (threshold } E_\nu = 0.23 \text{ MeV)}$
    - $\rightarrow$ sensitive to pp neutrinos
  - **Results**: 40 % of the expected signal

- **Real-time detection of (mostly) e- neutrinos**: **Kamiokande** (700 tons of water, 1983 – 1996), **Super-Kamiokande** (50 kt, 1996 –)
  - Reaction: $\nu_e + e^- \rightarrow \nu_e + e^-$ (emission of Cherenkov light)
  - **Results**: 40 % of the expected signal
Solution to the solar neutrino problem

Possible origin of the deficit

- Problem with the standard solar model? (3% of error on $T_c \rightarrow$ a factor of 2 in $N_v$)
- Problem with the nuclear data? $^7\text{Be}(p,\gamma)^8\text{B}$ cross-section
- New physics of neutrino $\rightarrow$ oscillation $\nu_e \rightarrow \nu_\mu, \nu_\tau$?

SNO: Sudbury Neutrino Observatory

- 1100 tons of $\text{D}_2\text{O}$ (99.9%)
- Sensitive to the three neutrino flavors
  $\rightarrow \nu_x + d \rightarrow p + n + \nu_x$ (neutral current)

(Bellerive+, NPB, 2016)

- Results: $\phi_{\text{NC}} = 5.21 \pm 0.27$ (stat) $\pm 0.39$ (sys) SNU
  in agreement with $\phi_{\text{SSM}} = 5.05^{+1.01}_{-0.81}$ SNU
4.2 Quiescent helium burning

- Where does it take place?
  - Core of horizontal branch stars (100 – 400 MK)
  - Burning shell in AGB stars (45 – 100 MK)

- Main nucleosynthesis products
  - $^4$He transformed in $^{12}$C and $^{16}$O for stars of more than $\sim 0.5 \, M_\odot$

- How does it work?
  - Mainly three reactions:
    - $\alpha + \alpha + \alpha \rightarrow ^{12}\text{C} \quad Q = 7.3 \, \text{MeV}$
    - $^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \quad Q = 7.2 \, \text{MeV}$
    - $^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne} \quad Q = 4.7 \, \text{MeV}$

- Who & when?
  - Triple alpha process: Öpik (1951), Salpeter (1952)
  - The “Hoyle” state in $^{12}$C: Hoyle (1953)
The triple alpha process

How are synthesized elements heavier than $^4\text{He}$, given that there are no stable isotopes for mass $A = 5$ ($p+\alpha$) and $A = 8$ ($\alpha+\alpha$)?

- Fusion of $3\alpha$ in $^{12}\text{C}$ in two steps
  - $\alpha + \alpha \leftrightarrow ^8\text{Be} \quad Q = -92 \text{ keV}$
    ($^8\text{Be}$ is unstable $\tau = 9.7 \times 10^{-17} \text{ s}$)
  - $\alpha + ^8\text{Be} \rightarrow ^{12}\text{C}^*$

- In view of the significant abundance of $^{12}\text{C}$ in the Universe (!), Hoyle (1953) predicted (i) that the reaction $\alpha + ^8\text{Be} \rightarrow ^{12}\text{C}^*$ is resonant and, (ii) the existence of a $J^\pi = 0^+$ state at 7.7 MeV in $^{12}\text{C}$

- Experimental verification in 1953 and 1957

Helium burning
The $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction

Slow and crucial reaction → Holy Grail in nuclear astrophysics

- The rate of this reaction determines the $^{12}\text{C}/^{16}\text{O}$ ratio at the end of the helium burning phase, and thus the subsequent burning stages in massive stars.

- $^{12}\text{C}/^{16}\text{O}$ influences the nature of the remnant (neutron star? Black hole?) left after a core-collapse supernova.

- A difficult case: contribution from a broad state, two sub-threshold resonances and the direct capture process.

- Cross-section at 300 keV

  $\sigma \approx 10^{-17}$ b! (can’t be measured, less than 1 event per year)
The $^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$ reaction

- Very slow reaction because no resonant state in the energy range of interest $5.0 \text{ MeV} < E_x^{(20}\text{Ne}) < 5.2 \text{ MeV}$ (the $J^\pi = 2^-$ state at $E_x = 4967 \text{ keV}$ being of non-natural parity)

- Reaction rate $<<$ rate of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ for $T < 0.3 \text{ GK}$
  $\Rightarrow$ end of the helium burning phase in stellar cores
  $\Rightarrow$ survival of $^{16}\text{O}$
How insignificant we are!

\[ Q(2\alpha \rightarrow ^8\text{Be}) = -92 \text{ keV} \]
\[ \Rightarrow \text{sufficient } ^8\text{Be} \text{ nuclei at equilibrium} \]

\[ J^\pi = 0^+, E_x = 7.65 \text{ MeV} \]
\[ \text{state of } ^{12}\text{C} \]
\[ \Rightarrow \text{“creation” of } ^{12}\text{C} \]

\[ \text{Sub-threshold } 1^- \text{ and } 2^+ \text{ states in } ^{12}\text{C} + \alpha \rightarrow ^{16}\text{O} \]
\[ \Rightarrow \text{“creation” of } ^{16}\text{O} \text{ but survival of } ^{12}\text{C} \]

\[ ^{20}\text{Ne state at 4.97 MeV of non-natural parity (2\text{'})} \]
\[ \Rightarrow \text{survival of } ^{16}\text{O} \]
Other reactions

- $^{14}\text{N}$ is the main “ash” from the CNO cycle, and accounts for 1-2% of the mass of the fusion core at the end of H burning (pop I stars)

  $\rightarrow ^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+\nu)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$

  followed by

  $\rightarrow ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ [= main source of neutrons of the weak s-process (“slow” neutron capture)]

- Helium burning is the main source of $^{12}\text{C}$, $^{16}\text{O}$, $^{18}\text{O}$ and $^{22}\text{Ne}$ in the Universe

Helium burning
4.3 Advanced nuclear burning phases

Schematic diagram of the “onion-skin” structure of a pre-supernova

Chandra X-ray observatory image of the SN remnant Cassiopeia A
Carbon burning

• When?
  • He exhausted in the stellar core → mainly $^{12}\text{C}$ and $^{16}\text{O}$ ashes → gravitational contraction → increase of temperature
  • $T_c \sim (5 – 9) \times 10^8$ K and $\rho > 2 \times 10^5$ g cm$^{-3}$ for $M \geq 8 M_\odot$

• Major reaction sequences
  $$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha \quad (Q = 4.62 \text{ MeV})$$
  dominates by far
  $$\rightarrow ^{23}\text{Na} + \text{p} \quad (Q = 2.24 \text{ MeV})$$
  $$\rightarrow ^{23}\text{Mg} + \text{n} \quad (Q = -2.62 \text{ MeV})$$
  + several secondary reactions..

• Composition at the end of core carbon burning
  • Mainly $^{20}\text{Ne}$ with some $^{21,22}\text{Ne}$, $^{23}\text{Na}$, $^{24,25,26}\text{Mg}$ and $^{26,27}\text{Al}$
  • $^{16}\text{O}$ not burning yet…. → amount comparable with $^{20}\text{Ne}$
Neon burning

- When?
  - After carbon burning → mainly $^{20}\text{Ne}$ ashes → the core further contracts → increase of temperature
  - $T_c \sim (1 - 2) \times 10^9 \text{ K}$ and $\rho \sim 10^6 \text{ g cm}^{-3}$ for $M \geq 11 M_\odot$

- Major reaction sequences
  - Temperatures are high enough to initiate photodisintegration processes
    \[
    \gamma + ^{20}\text{Ne} \rightarrow ^{16}\text{O} + \alpha \quad (Q = -4.73 \text{ MeV})
    \]
    \[
    ^{16}\text{O} + \alpha \rightarrow ^{20}\text{Ne} + \gamma
    \]
  - Followed by e.g. the $^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si}$ sequence

- Composition at the end of core neon burning
  - Mainly $^{16}\text{O}$ with some $^{24}\text{Mg}$ and $^{28}\text{Si}$
Oxygen burning

- **When?**
  - After neon burning the core further contracts
  - \( T_c \sim (2 – 3) \times 10^9 \text{ K} \) and \( \rho \sim 3 \times 10^6 \text{ g cm}^{-3} \) for \( M \geq 11 \text{ M}_\odot \)

- **Major reaction sequences**
  
  \[
  ^{16}\text{O} + ^{16}\text{O} \rightarrow ^{32}\text{S}^* \rightarrow ^{31}\text{S} + n \quad (Q = 1.45 \text{ MeV}) \\
  \rightarrow ^{31}\text{P} + p \quad (Q = 7.68 \text{ MeV}) \\
  \rightarrow ^{30}\text{P} + d \quad (Q = -2.41 \text{ MeV}) \\
  \rightarrow ^{28}\text{Si} + \alpha \quad (Q = -2.41 \text{ MeV})
  \]

  + recapture of n, p, d and \( \alpha \)-particles

- **Composition at the end of oxygen burning**
  - The most abundant nuclides are \( ^{28}\text{Si} \) and \( ^{32}\text{S} \)
Silicon burning

• When?
  • After oxygen burning the core further contracts and the temperature increases
  • \( T_c \sim (2.8 - 4.1) \times 10^9 \) K and \( \rho \sim 3 \times 10^7 \) g cm\(^{-3}\) for \( M \geq 11 \) M\(_\odot\)

• Photodisintegration
  • Starts with \( ^{28}\)Si: \( ^{28}\)Si(\(\gamma,\alpha\))\( ^{24}\)Mg(\(\gamma,\alpha\))\( ^{20}\)Ne(\(\gamma,\alpha\))…
  • Photodisintegration rearrangement: destruction of less tightly bound species and capture of released \( n, p, \alpha\)-particles to synthesize more tightly bound species

• Nuclear Statistical Equilibrium (NSE) is achieved for many reactions
  • NSE = both photodisintegration and capture rates are fast

\[
\begin{align*}
\gamma + (Z, N) & \rightleftharpoons p + (Z - 1, N) \\
\gamma + (Z, N) & \rightleftharpoons n + (Z, N - 1) \\
\gamma + (Z, N) & \rightleftharpoons \alpha + (Z - 2, N - 2)
\end{align*}
\]

• Equilibrium drives towards \( A = 56 \rightarrow \) most stable nuclide (higher binding energy)

• Synthesis of nuclei from Si to Zn ("iron peak" elements Ti to Zn)
• Composition at the end of silicon burning: \( ^{56}\)Fe \rightarrow formation of an iron core
## Summary

<table>
<thead>
<tr>
<th>Stellar mass (M_☉)</th>
<th>Stage reached</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.08</td>
<td>no thermonuclear fusion</td>
</tr>
<tr>
<td>0.1 - 0.5</td>
<td>H burning</td>
</tr>
<tr>
<td>0.5 - 8</td>
<td>He burning</td>
</tr>
<tr>
<td>8 - 11</td>
<td>C burning</td>
</tr>
<tr>
<td>&gt; 11</td>
<td>all stages</td>
</tr>
</tbody>
</table>

### Evolution stages of a 25 M_☉ star

<table>
<thead>
<tr>
<th>Stage reached</th>
<th>Timescale</th>
<th>T_{core} (10^9 K)</th>
<th>Density (g cm^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>H burning</td>
<td>7x10^6 y</td>
<td>0.06</td>
<td>5</td>
</tr>
<tr>
<td>He burning</td>
<td>5x10^5 y</td>
<td>0.23</td>
<td>7x10^2</td>
</tr>
<tr>
<td>C/O burning</td>
<td>600 y / 6 months</td>
<td>0.93 – 2.3</td>
<td>2x10^5 – 1x10^7</td>
</tr>
<tr>
<td>Si melting</td>
<td>1 d</td>
<td>4.1</td>
<td>3x10^7</td>
</tr>
<tr>
<td>Explosive burning</td>
<td>0.1 – 1 s</td>
<td>1.2 - 7</td>
<td>varies</td>
</tr>
</tbody>
</table>
4.4 Explosive nucleosynthesis

Massive stars

Binary systems

Type Ia supernova

G299 (Chandra X-ray observatory)

Classical nova

Nova Cygni 1992 (HST)
“Onion shell” structure of massive stars

Explosion:
- Core in NSE, grows in mass until $\sim 1.4 M_\odot$
- Collapse enhanced by photodisintegration ($\gamma + ^{56}{\text{Fe}} \rightarrow ^{13}{\text{He}} + 4n$) and electron capture ($e^- + (Z,N) \rightarrow \nu_e + (Z-1,N+1)$)
- Inner part of core rebounds $\rightarrow$ outward moving shock

Nucleosynthesis induced by neutrinos and outward moving shock (mainly in Si, O and Ne/C layers)
Core collapse supernova (2)

Light curve powered by radioactive decay

\[
\begin{align*}
M^{(44}\text{Ti}) &= 3.80 \times 10^{-5} M_\odot \\
M^{(55}\text{Co}) &= 1.30 \times 10^{-4} M_\odot \\
M^{(56}\text{Ni}) &= 6.90 \times 10^{-2} M_\odot \\
M^{(57}\text{Ni}) &= 2.43 \times 10^{-3} M_\odot \\
M^{(60}\text{Co}) &= 4.00 \times 10^{-5} M_\odot
\end{align*}
\]

\[\text{SN 1987A}\]

- \(\text{Ni}^{56} \rightarrow \text{Co}^{56} \rightarrow \text{Fe}^{56}\) (stable)
  - \((T_{1/2} = 6.1 \text{ d})\)
  - \((T_{1/2} = 77.3 \text{ d})\)

- \(\text{Ti}^{44} \rightarrow \text{Sc}^{44} \rightarrow \text{Ca}^{44}\) (stable)
  - \((T_{1/2} = 60 \text{ yr})\)
  - \((T_{1/2} = 3.97 \text{ h})\)

\[\text{Cas A}\]

\[\text{SN 1987A}\]
Classical novae (1)

Sudden increase in star’s luminosity \((L \sim 10^4 – 10^6 \, L_i, \text{ and } t \sim 1\,\text{h} – 1\,\text{d})\)

Final evolution of a close binary system

- **H-rich material transfer** from normal star to white dwarf (WD)
- **\(T\) and \(\rho\) increase** at surface of WD
- **Start and thermonuclear runaway** \((T \approx 50 – 300 \, \text{MK})\)
  - \(\rightarrow\) cataclysmic explosion
- **Ejection** of part of the accreted material

<table>
<thead>
<tr>
<th></th>
<th>novae</th>
<th>ccSN</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M_{\text{ej}} (M_\odot))</td>
<td>(\sim 10^{-5})</td>
<td>(\sim 10)</td>
</tr>
<tr>
<td>(f , (\text{yr}^{-1} , \text{galaxy}^{-1}))</td>
<td>(\sim 30)</td>
<td>(\sim 10^{-2})</td>
</tr>
<tr>
<td>(L , (L_\odot))</td>
<td>(\sim 10^5)</td>
<td>(\sim 10^{11})</td>
</tr>
<tr>
<td>Nucleosynthesis</td>
<td>(^{13}\text{C}, , ^{15}\text{N}, , ^{17}\text{O})</td>
<td>(~ \text{all})</td>
</tr>
</tbody>
</table>
Shell ejection
The energy release from the $\beta^+$-decays ($^{13}$N, $^{14}$O, $^{15}$O, $^{17}$F) throughout the envelope helps to eject the material from the WD

End-point of nucleosynthesis: $A \sim 40$ (Ca)
- $T_{peak} \sim 300 – 400$ MK
- $(p,\gamma)$ reactions on the proton-rich side
- Coulomb barrier too high to overcome for $A \geq 40$

Nucleosynthesis of $\gamma$-ray emitters
- $^{18}$F ($T_{1/2} = 110$ min); 511 keV
- $^{22}$Na ($T_{1/2} = 2.6$ yr); 1275 keV
- $^{26}$Al ($T_{1/2} = 0.7$ Myr); 1809 keV
4.5 Nucleosynthesis beyond iron

Elements heavier than iron can’t be synthesized by fusion reactions.
Neutron capture reactions

- Radiative neutron captures \([n,\gamma]\) reactions in competition with \(\beta^–\) decay
- Processus starts with Fe seeds

![Diagram showing neutron capture processes]

- Mean lifetime for neutron capture \(\tau_n = \frac{1}{N_n \langle \sigma v \rangle}\) to be compared to \(\beta^–\)-decay lifetime \(\tau_\beta\) (from seconds to years)
- If \(\tau_n > \tau_\beta\) → unstable nuclide decays
- If \(\tau_n < \tau_\beta\) → neutron capture

s-process: “slow”
r-process: “rapid”
- **Slow neutron capture process**
  - Unstable nucleus decays *before* capturing another neutron
  - $\tau_n \gg \tau_\beta \iff N_n \sim 10^8 \text{ n/cm}^3$

- **Nucleosynthesis**: path along the valley of $\beta^-$ stability up to $^{209}\text{Bi}$ (long time scale $\sim 10^4$ yr)
- **Neutron source**: $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and/or $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
- **Quiescent scenarios**:  
  - *AGB stars*: main s-process; “Ba/Pb” peaks
  - *Massive stars*: weak s-process; “Sr-Y” peak

![Diagram of the s-process with elements and nuclear reactions.](attachment:image.png)
- Rapid neutron capture process
  - Unstable nucleus captures neutron before decaying
- $\tau_n < < \tau_\beta \iff N_n >> 10^{22} \text{ n/cm}^3$

- Nucleosynthesis: path far from the valley of $\beta^-$ stability (short time scale $\sim$ seconds)
- Explosive scenarios: but where?
Astrophysical site for $r$-process?

Core-collapse Supernovae?  

- Dynamical ejcta of prompt explosions (of O-Ne-Mg cores)
- Neutrino-driven wind from proto-neutron stars
- ...

Supernova SN1987A

Neutron star merger?

- Mergers are expected to eject $\sim 0.01 \, M_\odot$ of very neutron-rich material
- Sources of gravitational waves
- Electromagnetic emission from radioactive decay of $r$-process nuclei $\rightarrow$ kilonova

Neutron captures
Neutron star merger GW170817

- Gravitational waves from neutron star merger detected by LIGO/VIRGO

Two neutron stars of $0.86 \, M_\odot$ and $2.26 \, M_\odot$

- Optical transient source counterpart SSS17a (Swope Supernova Survey)

Counterpart in galaxy NGC4993 at $\sim 40 \, \text{Mpc}$

- First day
  - blue and bright

- Four days later
  - red and fainter

Neutron captures
Near-infrared emission

Comparison of the measured near-infrared spectrum counterpart of the binary neutron star merger GW170817 with a “red” kilonova model

- The two bumps in the near infrared spectrum is a signature of very heavy elements
- Effect of opacity induced by lanthanide elements
- Lanthanides (~ 1%)
  → \( r \)-process
5. Back to the HR diagram

Main sequence star:
H $\rightarrow$ He core burning via the pp chains

Horizontal branch star:
He $\rightarrow$ C, O core burning + H $\rightarrow$ He shell burning

Red giant star:
H $\rightarrow$ He shell burning via the CNO cycle

Globular cluster M10
Red giant stars (1)

- Stars of mass $0.5 - 10 \, M_\odot$ (if $M \geq 10 \, M_\odot \rightarrow$ red supergiants)
- Inert He core (no energy source) surrounded by a H burning shell

From the Virial theorem

$$E = K + \Omega = \Omega/2 = -K$$

If $E \sim \text{cst}$, $\Omega$ and $K$ also

$\rightarrow$ contraction of the core must be accompanied by expansion of the envelope ($\Omega \sim \text{cte}$) up to $50 \, R_\odot$ ($\sim$ Mercury)

$\rightarrow$ core heating must result in cooling of the envelope ($K \sim \text{cte}$) $\rightarrow T_{\text{eff}}$ decreases

$\rightarrow L = 4\pi R^2 \sigma_s T_{\text{eff}}^4$ increases

Back to HR
Red giant stars (2)

- Decrease of $T_{\text{eff}}$ → recombination in stellar atmosphere → increase of opacity → radiative transport less efficient → convection settles in envelope
- Ashes of H-shell burning – $^{13}$C, $^{14}$N – are transported to the surface → first “dredge-up”
  → high $^{13}$C/$^{12}$C and $^{14}$N/$^{12}$C isotopic ratios observed in absorption spectra of red giant stars

Back to HR
Stars of the horizontal branch (1)

**Ignition of the He core at** $T_c \sim 100$ MK → core contraction stops

- In low-mass stars ($0.7 - 2 M_\odot$) the electron gas in the core is partially degenerated → helium flash

  → release during a few seconds of $10^{10} L_\odot$ in $L_{\text{nuc}}$! but invisible from the surface

  → expansion and cooling of the core result in the contraction and heating of the envelope

Back to HR
Stars of the horizontal branch (2)

- **Quiet ignition** of the He core (convective) for intermediate-mass stars ($2 - 10 \, M_\odot$)

Ignition of the He core at $T_c \sim 100 \, \text{MK} \rightarrow$ core contraction stops
AGB stars

- Asymptotic Giant Branch (AGB); E-AGB = early AGB
- Inert C/O core (no energy source) left after He core burning
- He burning shell + H burning shell
- Convective envelope → second “dredge-up” (H-burning ashes are brought to the surface by convection)

- As for red giant phase, radius is increasing..... up to $200 \, R_\odot$ (~ Earth)!

![Diagram showing layers of AGB star, with layers labeled H → He, He shell, He → C+O, C+O core, and Convective envelope.]
TP-AGB stars (Thermal Pulses)

- Mixing of ashes from H and He burning
- Site of the main s-process
### Evolution of a solar-type star

<table>
<thead>
<tr>
<th>Time until the next stage (year)</th>
<th>$T_c$ (MK)</th>
<th>$T_{\text{eff}}$ (K)</th>
<th>$\rho_c$ (g cm$^{-3}$)</th>
<th>Radius ($R_\odot$)</th>
<th>Stellar stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{10}$</td>
<td>15</td>
<td>6000</td>
<td>$10^2$</td>
<td>1</td>
<td>Main sequence</td>
</tr>
<tr>
<td>$10^8$</td>
<td>50</td>
<td>4000</td>
<td>$10^4$</td>
<td>3</td>
<td>Subgiant</td>
</tr>
<tr>
<td>$10^5$</td>
<td>100</td>
<td>4000</td>
<td>$10^5$</td>
<td>50</td>
<td>Helium flash</td>
</tr>
<tr>
<td>$5 \times 10^7$</td>
<td>200</td>
<td>5000</td>
<td>$10^4$</td>
<td>10</td>
<td>Horizontal branch</td>
</tr>
<tr>
<td>$10^4$</td>
<td>250</td>
<td>4000</td>
<td>$10^5$</td>
<td>200</td>
<td>AGB</td>
</tr>
<tr>
<td>$10^5$</td>
<td>300</td>
<td>100 000</td>
<td>$10^7$</td>
<td>0.01</td>
<td>Compact star enriched in C, O (planetary nebula)</td>
</tr>
<tr>
<td>-</td>
<td>100</td>
<td>50 000</td>
<td>$10^7$</td>
<td>0.01</td>
<td>White dwarf</td>
</tr>
</tbody>
</table>
Summary
Abundance curve and processes

- Big Bang nucleosynthesis
  - Fusion reactions (exothermic)
  - Neutron-capture reactions (s-, r-process)
- Stellar nucleosynthesis
- Cosmic-ray produced

Solar abundance ($^{28}\text{Si} = 10^6$)

Mass number $A = Z + N$
Nuclear landscape and astrophysical processes

- Neutron number
- Proton number

- BBN
- Classical novae
- Fusion
- X-ray bursts: $\alpha p$, rp-process
- Classical novae
- Cosmic-rays

- p-process
- s-process
- r-process

Known nuclides ~ 3760
- Stable ~ 255
- Unstable ~ 3505
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