Lecture plan

- Lecture 1
  - Solar system abundances
  - A tiny little bit of BBN
  - Hydrostatic nuclear burning
  - Thermonuclear reaction rates

- Lecture 2
  - Supernovae
  - Explosive nuclear burning
  - Heavy element synthesis
  - Spectroscopy and metal-poor stars
Summary from lecture 1
Supernovae

Supernovae are violent explosions at the end of a star's life, which can be classified into different types based on their properties and the cause of the explosion. Here are a few examples:

- **SN 1987a**: This supernova was discovered in 1987 and is known for being the first supernova to be imaged in the ultraviolet and X-ray bands.
- **SN 2010fe**: This supernova was observed in 2010 and is one of the brightest supernovae recorded.
- **SN 2007uy**: This supernova was observed in 2007 and is notable for its fast decline in brightness.

Optical transients discovery by CRTS

CSS Optical transient (GRB candidate)
Supernova Classification

- (Spectral) Appearance
  - Type I
    - Subtypes: a, b, c
  - Type II

- Mechanism:
  - Thermonuclear
  - Core-collapse

- Brightness
  - “normal”
  - superluminous
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Type Ia supernovae

- White dwarf in a binary system with a ...
  - Main-sequence star (single-degenerate scenario)
  - White dwarf (double-degenerate scenario)
- Synthesize mostly iron via explosive burning
  - About 2/3 of total iron is from type Ia SNe
Core-collapse supernovae (CCSNe)

Stellar burning
\[ \rightarrow C, O \]
Weak s-process
\[ \rightarrow \text{heavy elements} \]
Explosion mechanism still not fully understood

Explosive burning
\[ \rightarrow Si, S, Ca, Fe, Ni, Zn \]
\[ \nu p\text{-process} \]
\[ \rightarrow Sr, Y, Zr + Mo, Ru \]
\[ \gamma\text{-process} \]
\[ \rightarrow p\text{-nuclides} \]
Pair-instability supernovae (PISNe)

- Also called: Pair-creation supernovae
- Very massive stars (>100 Msun)
- Oxygen-core becomes unstable via \( 2\gamma \rightarrow e^+ + e^- \)
  - Remove radiation pressure \( \rightarrow \) core collapses \( \rightarrow \)
    explosive oxygen burning reverses collapse \( \rightarrow \)
    explosion
Supernovae happen when evolution reaches region of instability.

Langer (2012)
Explosive nuclear burning

- Similar to hydrostatic burning, but
  - Shorter timescales
  - Higher temperatures

- H-burning:
  - Hot CNO-cycle (pp-chains are too slow), where $^{13}\text{N}(\beta)$ becomes $^{13}\text{N}(p,\gamma)$

- He-burning:
  - N-rich isotopes $^{15}\text{O}$, $^{18}\text{O}$, $^{19}\text{F}$, $^{21}\text{Ne}$

- C- and Ne-burning:
  - Simultaneously occurring
Explosive burning

- O-burning:
  - Quasi-equilibrium (regions of equilibrium, connected by individual reactions)

- Si-burning:
  - Details depend on peak temperature and peak density:
CCSN nucleosynthesis

Simulations (computationally very expensive; not fully converged yet in outcome):

Textbook:
- Add energy to pre-collapse star to trigger explosion (piston, thermal bomb, neutrinos)
- But: Ignores some physics (collapse, bounce, neutrinos, NS/BH formation, etc)

Reality:
- We observe stars and SNe
- We still do not fully understand the explosion mechanism despite 60+ years of research

Practical approach:
Modelling of CCSN nucleosynthesis

- Piston / thermal bomb
  - Woosley&Weaver 95, Rauscher+02
  - Thielemann+96, Limongi & Chieffi 06, Umeda&Nomoto 08

- Neutrinos methods
  - Light bulb
    - Iwakami+09, Yamamoto+13
  - Modified neutrino reactions
    - Frohlich+06, Fischer+10
  - Parameterized PNS contraction
    - Ugliano+12, Ertl+15, Sukhbold+16
  - PUSH method
    - Based on neutrino-driven mechanism (use neutrinos to obtain explosion)
    - Preserve Ye evolution (no modification of $\nu_e$-transport)
    - Nuclear EOS and PNS evolution included
Results using the PUSH method

- Calibrated against SN 1987A
- Progenitor mass, explosion energy, Ni and Ti ejecta

Ebinger+ (in prep)
Results using the PUSH method

- Calibrated against SN 1987A
  - Progenitor mass, explosion energy, Ni and Ti ejecta
- Applied to models from 11 Msun to 40 Msun
  - Predict some explosions and some BHs

Ebinger+ (in prep)
Comparison to other methods

Ebinger+ (in prep)

Pechja+2015

Sukhbold+2016

Mueller+2016
Results using the PUSH method

- Calibrated against SN 1987A
  - Progenitor mass, explosion energy, Ni and Ti ejecta

- Applied to models from 11 Msun to 40 Msun
  - Predict some explosions and some BHs

- Nucleosynthesis predictions
  - Better match to observations than piston models
Metal-poor star HD 84937

\[
\frac{X}{X_{\text{Fe}}} = \log \left( \frac{X}{X_{\text{Fe}}} \right) - \log \left( \frac{X}{X_{\text{Fe}}} \right)
\]

Sneden+16

Sanjana+ (in prep)
Metal-poor star HD 84937

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\left[ \frac{X}{X_{\text{Fe}}} \right] = \log \left( \frac{X}{X_{\text{Fe}}} \right) - \log \left( \frac{X}{X_{\text{Fe}}} \right)
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\]

Sneden+16

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Metal-poor star HD 84937

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Sneden+16

Sanjana+ (in prep)
Origin of elements

**Big Bang**

- Hydrogen
- Helium

**Stellar burning**

- Iron Group

**Solar system abundances**

- $\alpha$-elements ($^{12}\text{C}$, $^{16}\text{O}$, ...)

![Graph showing the distribution of elements by atomic mass and log N (solar system)]
Neutron-capture processes

Heavy elements are made by
- slow \((\tau_\beta/\tau_n < 1)\)
- fast \((\tau_\beta/\tau_n > 1)\)
neutron-capture events

- Sequences of \((n,\gamma)\) reactions and \(\beta^-\)decays

\[
\begin{align*}
A(Z, N) + n &\leftrightarrow A + 1(Z, N + 1) + \gamma \\
A(Z, N) &\rightarrow A(Z + 1, N - 1) + e^- + \bar{\nu}_e
\end{align*}
\]
Neutron-capture paths

- (n,γ) reactions
- β⁻-decays

N=82 closed neutron-shell
Neutron-capture paths

- **Number of neutrons**
- **Number of protons**

- N=82 closed neutron-shell

- Ba Te
- Xe

- s-process path

- β-decay to stability at the end

- r-process path

- N=82 closed neutron-shell
Neutron-capture processes

heavy elements are made by
slow \((\tau_{\beta}/\tau_{n} < 1)\)
and
fast \((\tau_{\beta}/\tau_{n} > 1)\)
neutron-capture events

- Sequences of \((n,g)\) reactions and \(\beta^{-}\)decays
  \[
  A(Z, N) + n \leftrightarrow A + 1(Z, N + 1) + \gamma
  \]
  \[
  A(Z, N) \rightarrow A(Z + 1, N - 1) + e^{-} + \bar{\nu}_{e}
  \]

- Closed neutron-shells give rise to the peaks at \(\text{Te, Xe} / \text{Ba}\) and at \(\text{Os, Pt, Au} / \text{Pb}\)
The s-process

- Secondary process
  → neutron captures on pre-existing Fe-group nuclei

- Strong s-process (up to Pb)

- Weak s-process (truncated at Z~60)
The strong s-process

- He-shell flashes in AGB stars
Strong s-process

Low mass AGBs
Lower temperature \( \sim 4.5 \, M_\odot \)
Larger intershell mass

Intermediate mass AGBs
Higher temperature
Smaller intershell mass

ENVELOPE

He intershell
base of convective envelope

H-burning shell
C-O CORE

\( \alpha(n,\gamma) \)
proton diffusion
convective pulse
drudge-up

\( ^{13}\text{C}(\alpha,n)^{16}\text{O} \)

\( ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \)

Slide from Karakas & Lugaro
The s-process

- Secondary process
  \[ \text{neutron captures on pre-existing Fe-group nuclei} \]

- Strong s-process (up to Pb)
  - He-shell flashes in AGB stars
  - Protons are mixed from H-shell; produce \(^{13}\text{C}\)
  - During He-burning: \(^{13}\text{C} + \alpha \rightarrow ^{16}\text{O} + \text{n}\)
    \[ \rightarrow \text{strong neutron source} \]

- Weak s-process (truncated at \(Z\sim60\))
  - Core burning in massive stars:
    - He-burning (1-2 \(\times\) 10\(^8\)K)
      \[ ^{14}\text{N(\alpha,y)18F(\beta^+)18O(\alpha,y)22Ne(\alpha,n)25Mg} \]
    - C-burning (6-8 \(\times\) 10\(^8\)K)
      \[ ^{12}\text{C(p,y)13N(\beta^+)13C} \]
      \[ ^{13}\text{C(\alpha,n)16O} \]
      \[ \text{p from } ^{12}\text{C(}^{12}\text{C,p)23Na} \]
      \[ \alpha \text{ from } ^{12}\text{C(}^{12}\text{C,}\alpha)20\text{Ne} \]
The weak s-process

Overproduction factors of 25 $M_\odot$ models with $Z = 10^{-5}$ ($[\text{Fe}/\text{H}] = -3.8$)

Seed nuclei and neutron sources are secondary, neutron poisons are primary!
The r-process

1\textsuperscript{st} peak: $A\sim80$ ($N=50$)
2\textsuperscript{nd} peak: $A\sim130$ ($N=82$)
3\textsuperscript{rd} peak: $A\sim195$ ($N=126$)

Primary process!
The r-process site

• Most important criteria for an r-process site:
  • High neutron density
  • Eject material

• Neutron sources:
  • Neutrons in nuclei (must be liberated)
  • Neutron stars
  • Made through weak reactions

• Conditions:
  • High entropy, alpha-rich freeze-out
  • Low entropy, normal freeze-out with very low Ye
The r-process site(s)

- Neutrino-driven wind in CCSNe
- ONeMg core collapse
- Quark-hadron phase transition
- Explosive He-burning in outer shells
- Charged-current neutrino interactions in outer shells
- Polar jets from rotating CCSNe
- Neutron-star mergers
- BH accretion disks
The $r$-process site(s)

- Neutrino-driven wind in CCSNe
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No?!
weak
If? Weak!
???
Abundance pattern??
Promising; initial conditions??
Neutrino-driven winds in CCSNe

\[ T = 10^{-8} \text{ GK} \]

- NSE

\[ T = 8 - 2 \text{ GK} \]

- charged-particle reactions;
- \( \alpha \)-process

\[ T < 3 \text{ GK} \]

- (weak) r-process
- vp-process
Wind conditions for r-process

- High neutron-to-seed ratio: \( Y_n/Y_{seed} \sim 100 \)
- Short expansion timescale: \( 10^{-3} \) to 1 second
  \( \rightarrow \) inhibits formation of nuclei through \( \alpha \)-process
- High entropy: \( s/k_B \sim 20 – 400 \)
  \( \rightarrow \) many free nucleons
- Moderately low electron fraction: \( Ye < 0.5 \)

**BUT**: Conditions not realized in recent simulations

Simulations find:
- \( \tau \sim \) few milliseconds
- \( s \sim 50-120 \) \( k_B/\text{nuc} \)
- \( Ye \sim 0.4 – 0.6 \)

\( \rightarrow \) Additional ingredients??
Magneto-rotational SNe

3D collapse of fast rotator with strong magnetic fields:

15 Msun progenitor
Shellular rotation with period of 2s at 1000km
Magnetic field in z-direction of $5 \times 10^{12} \ G$
Kaeppeli, Winteler, Liebendoerfer 2014
Eichler+2014 (nucleosynthesis)

3D collapse of fast rotator with strong magnetic fields:

25 Msun progenitor
Magnetic field in z-direction of $10^{12} \ G$
Moesta+2014

$\beta = \frac{P_{\text{gas}}}{P_{\text{mag}}}$
Nucleosynthesis from rot. CCSNe

- r-process peaks well reproduced
- Trough at A=140-160 due to FRDM and fission yield distribution
- A = 80-100 mainly from higher Ye
- A > 190 mainly from low Ye
- Ejected r-process material (A > 62):

\[ M_{r,ej} \approx 6 \times 10^{-3} \, M_\odot \]
Neutron-star mergers

- 3rd peak always shifted to heavier nuclei (trajectories too neutron-rich)
Chemical evolution

Magenta: data
No magnetorotational jets
Green/red: different merging time scales
Blue: higher merger rate

Wehmeyer+ (2015)
The r-process site(s)

- Neutrino-driven wind in CCSNe
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No?!
weak
If? Weak!
??
Abundance pattern??
Promising; initial conditions??
Will results hold with improved simulations??
Origin of elements

- Hydrogen
- Helium

Big Bang

Stellar burning

Solar system abundances

- Iron Group
- α-elements ($^{12}$C, $^{16}$O, ...)
- r-process
- s-process
The neutron-capture processes

The neutron-capture processes involve the capture of neutrons by atomic nuclei to form elements with higher atomic numbers. These processes are categorized into s-process, r-process, and p-process based on the neutron-capture rates and the energy sources involved.

- **s-process**: Occurs in low-mass stars and involves the capture of neutrons by stable nuclei, leading to the production of elements with high atomic numbers. The lifetimes of elements produced in the s-process are typically long, with some lifetimes exceeding $10^{10}$ years.

- **r-process**: Occurs in high-mass stars and involves the capture of neutrons by unstable nuclei, leading to the production of elements with very high atomic numbers. The lifetimes of elements produced in the r-process are very short, with some lifetimes being less than 1 second.

- **p-process**: Occurs in neutron-rich environments and involves the capture of neutrons by unstable nuclei, leading to the production of elements with intermediate atomic numbers. The lifetimes of elements produced in the p-process are intermediate between those of the s-process and r-process.

The diagram above illustrates the neutron-capture processes for elements with atomic numbers ranging from 174 to 190, showing the movement of isotopes through the processes and the production of stable and unstable elements.
The p-process (for the p-nuclei)

Now understood to be several processes:

- **γ-process**: photodisintegration of pre-existing heavy nuclei
- **ν-process**: \((\nu, \nu')\) or \((\nu, e^-)\)
- **νp-process**: \(p(\nu, e^+)n\) followed by \((n, p)\)

Suggested by Arnould (1976) and Woosley&Howard (1978)
The $\gamma$-process

- Photodisintegrations of pre-existing heavy (s-process) nuclei
- In thermal bath of supernova explosions in explosive Ne/O burning layers with peak temperatures of $2-3 \times 10^9$ K
The $\gamma$-process

- Photodisintegrations of pre-existing heavy nuclei (from previous s-process event)
- In thermal bath of supernova explosions in explosive Ne/O burning layers with peak temperatures of $2-3 \times 10^9$ K

The $\gamma$-process

- Predicted p-nuclei overproduction

$\frac{\langle \gamma \rangle}{\langle \gamma \rangle_0}$

$\frac{\langle \gamma \rangle}{\langle \gamma \rangle_0}$

$\frac{\langle \gamma \rangle}{\langle \gamma \rangle_0}$


$\rightarrow$ Underproduction of light p-nuclei

Arnould & Goriely (2003)
Origin of elements

Big Bang

Hydrogen

Helium

Stellar burning

Iron Group

Solar system abundances

r-process

s-process

p-nuclei

α-elements ($^{12}$C, $^{16}$O, ...)

53

Hydrogen

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Trends with metallicity

Significant scatter at low metallicities

r-process is rare in early Galaxy
The oldest observed stars

Larger scatter

Robust r-process pattern

Figure: John Cowan (2011)
LEPP: Lighter Element Primary Process

- Observations of halo stars indicate two “r-process” sites:
  - Main r-process
  - Stellar LEPP / weak r-process

![Graph showing the distribution of heavy r-process abundances in stars.](image)

Stars with high enrichment in heavy r-process abundances

Stars with low enrichment in heavy r-process abundances
LEPP: Lighter Element Primary Process

- Observations of halo stars indicate two “r-process” sites:
  - Main r-process
  - Stellar LEPP / weak r-process

- Solar LEPP
  - Explains underproduction of “s-only” isotopes from Mo to Xe
  - Contributes 20-30% of solar Sr, Y, Zr
  - Solar abuns = r-process + s-process + LEPP

- Stellar LEPP
  - Same as solar LEPP?

Travaglio et al (2004): LEPP (solar LEPP)
Montes et al (2007)
The \( \nu p \)-Process

- proton-rich matter is ejected under the influence of neutrino interactions
- true rp-process is limited by slow \( \beta \) decays, e.g. \( \tau(64\text{Ge}) \)
- Neutron source:
  \[
  \bar{\nu}_e + p \rightarrow n + e^+ 
  \]
- Antineutrinos help bridging long waiting points via \((n,p)\) reactions:
  \[
  \begin{align*}
  64\text{Ge} &\rightarrow (n,p)\rightarrow 64\text{Ga} \\
  64\text{Ga} &\rightarrow (p,\gamma)\rightarrow 65\text{Ge}
  \end{align*}
  \]
The $\nu p$-Process

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- true rp-process is limited by slow $\beta$ decays, e.g. $\tau(64\text{Ge})$
- Neutron source:
  \[ \bar{\nu}_e + p \rightarrow n + e^+ \]
- Antineutrinos help bridging long waiting points via $(n,p)$ reactions:
  
  $64\text{Ge} \ (n,p) \ 64\text{Ga}$
  $64\text{Ga} \ (p,\gamma) \ 65\text{Ge}$

Heavy element synthesis inventory

- **s-process**
  - Secondary process; in AGB stars up to Pb or in massive stars as weak s-process

- **γ-process**
  - Secondary process; underproduction of light p-nuclei

- **r-process**
  - Primary process; probably some combination of MHD SNe and NS-mergers?
  - ???

- **vp-process**
  - In proton-rich neutrino winds
Summary

Astrophysical sites:

- Stellar evolution of low-mass and massive stars
- AGB stars (main s-process)
- Core He-burning of massive stars (weak s-process)
- Supernovae (explosive burning)
  - CC supernovae (γ-process)
  - CC supernovae (vp-process)
- Jets in magn-rot. SNe (r-process)
- NS mergers (r-process)
- X-ray bursts (rp-process)