Nucleosynthesis
The Making of the Chemical Elements

Advisor Seminar Physik-Departement TU München
Dozenten der Astrophysik

SS 2004

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Overview: Themes and Topics

★ Astrophysical Environments of Nuclear Reactions
   ➢ Nuclear Reactions of Thermalized Particles
   ➢ Elementary Reaction Types
   ➢ Reaction Networks, Equilibria, Freeze-Out

★ Characteristic Cosmic Nucleosynthesis Sites
   ➢ The Post-Big-Bang Area (BBN)
   ➢ Stellar Cores and Shells, Hydrostatic Nuclear Burning
   ➢ SNIa Explosions: Nuclear Statistical Equilibrium and Freeze-Out
   ➢ Core Collapse: Explosive Burning in Shock Regions, ν Process
   ➢ Compact Star Surfaces: Novae and X-Ray Bursts
   ➢ Neutron Capture Sites (cc-SNe, He Shells): r,s-Processes
   ➢ Energetic Collisions in Interstellar Space, Near Compact Stars

★ Measurements of Isotopic Abundances
   ➢ Meteorites, Stellar Atmospheres
   ➢ Interstellar Gas
   ➢ Hot Plasma, Radioactivities

★ Cycles of Matter
   ➢ Chemical Evolution of Local Regions, Galaxies, Clusters
“Structures” of Matter at Different Scales

Varieties of Appearances of Matter on Scales between Micro- and Macro-Cosmos:
- “elementary” Building Blocks
- “large-scale” Structures, Universes

Elementary Particles
- n, p
- Hadrons
- Leptons
- e⁻, ν

Atomic Nuclei

Molecules

Isotopes

Stars, Galaxies

Dust...Solids
...biological Bodies

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Cosmic Element Formation Studies

Goals:

☆ Understand the Physical Processes which Shaped the Pattern of Abundances in (different parts of) the Universe
☆ Identify & Model the Cosmic Sites of Nucleosynthesis
☆ Understand Mixing Processes of Matter on Cosmic Scales

Standard Abundances

Abundance (log N, H=12) vs. Element (Z)

fragile elements

α elements

Fe group elements (most tightly bound)
tighter-bound elements (closed shells)
Cosmic Nucleosynthesis: The Issues

- Nuclear Structure, Nucleon Interactions
  - Coulomb Repulsion versus Strong Interaction
  - Collective Interactions, Clusters

- Reaction Path far from Stability
  - No Data from Nuclear-Physics Experiments
  - Lessons on Nuclear Physics from Astronomy

- Cosmic Environments of Nuclear Reactions
  - Explosive Heating & Burning Zone Dilution
  - Longterm Evolutions in Stars (Convection) and Interstellar Medium ("chemical evolution")

"Nuclear Astrophysics"

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Nucleosynthesis: Understanding Abundances

☆ Observed Abundances Show Characteristic Patterns

- Abundances Vary Much for Light Elements up to ~ Fe-Group, are ~Similar Order of Magnitude for Elements >65
- H and He are by far the Most Abundant Elements
- Li, Be, B Fall in a Deep Minimum (9 Orders of Magnitude)
- Elements C….Ca Show Exponentially-Declining Abundances
- There is a Abundance Clear Peak Around Fe
- There are Two Local Peaks Around Ba and Pb

☆ Nuclear Processes / Reactions “Connect” Neighbouring Isotopes (Reactions $\rightarrow$ n, p, or $\alpha$ capture or stripping)

⇒

- Big-Bang Nucleosynthesis Formed H and He
- Nuclear Equilibrium Burning Formed Fe Elements
- An “$\alpha$-Process” Plays a Leading Role for Elements C…Ca
- Elements Heavier Than Fe Formed from Fe Elements
## Nucleosynthesis: “Processes”, “Categories”

<table>
<thead>
<tr>
<th>Process</th>
<th>Site</th>
<th>Key Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>H burning</td>
<td>pp chains, CNO cycle</td>
<td>all stars</td>
</tr>
<tr>
<td>He burning</td>
<td>3-α process</td>
<td>most stars</td>
</tr>
<tr>
<td>α-process</td>
<td>hot burning with excess α’s</td>
<td>mass. stars, SNaes</td>
</tr>
<tr>
<td>Fe-group elements:</td>
<td>e-process thermal equilibrium (NSE)</td>
<td>SNae (thermonucl)</td>
</tr>
<tr>
<td>Fe-group elements:</td>
<td>s-process n capt. slower than β-decay</td>
<td>He-burning stars</td>
</tr>
<tr>
<td>Fe-group elements:</td>
<td>r-process n capt. faster than β-decay</td>
<td>SNae (CC)</td>
</tr>
<tr>
<td>spallation</td>
<td>energetic heavy-ion collision</td>
<td>ISM / cosmic rays</td>
</tr>
<tr>
<td>p-rich isotopes:</td>
<td>rp-process hot H burning</td>
<td>novae</td>
</tr>
<tr>
<td></td>
<td>p-process n depletion ('γ-process')</td>
<td>??</td>
</tr>
<tr>
<td>‘normal’ nuclear reactions</td>
<td>[(n,γ), (p,γ), (α,γ)]…</td>
<td>stars, SNaes</td>
</tr>
<tr>
<td>ν-process</td>
<td>ν excitation of nuclei</td>
<td>SNae (CC)</td>
</tr>
<tr>
<td>x-process</td>
<td>unknown; make up for ??</td>
<td>various contributions</td>
</tr>
</tbody>
</table>

*BBN+Spallation deficiency

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Origin and fate of the elements in our universe

Nuclear Physics and Astrophysics
Nuclear Burning Requirements:

- \( \langle \sigma v \rangle \times Q \geq \text{Local Cooling Rate} \)

\( \Rightarrow \)

- Dense & Hot Environments

for a Stellar Mass Range of 1-30 \( M_\odot \):

- Nuclear Burning in Stellar Cores and Shells (top)
- Nuclear Burning in Explosive Sites (bottom)
- Gamov Windows (righthand side)
Big Bang Nucleosynthesis

A cosmic census of baryons. The light element abundances predicted by BBN theory are shown in red as a function of cosmic baryon density (expressed as a fraction $\Omega_\text{b}$ of the "critical" density required to prevent the universe from expanding forever). The observed range of each light element’s abundance sets the height of the three boxes. For each element, the observed data range and the theory curves combine to select a domain in $\Omega_\text{b}$, shown as the horizontal range of the box. The vertical overlap of the boxes thus gives the range in $\Omega_\text{b}$ for which BBN theory and observations agree. This is the BBN measurement of cosmic baryons (yellow band). The CMB range for $\Omega_\text{b}$ (green band) agrees with the BBN result.
Elementary Nuclear-Reaction Cycles

- H Burning: p-p Chains

\[ \begin{align*}
\mathrm{^{1}H} & + \mathrm{p} \rightarrow \mathrm{^{2}D} \\
\mathrm{^{2}D} & + \mathrm{p} \rightarrow \mathrm{^{3}He} \\
\mathrm{^{3}He} & + \mathrm{p} \rightarrow \mathrm{^{4}He} + \gamma \\
\mathrm{^{4}He} & + \mathrm{p} \rightarrow \mathrm{^{7}Be} + \gamma \\
\mathrm{^{7}Be} & + \mathrm{e^{-}} + \mathrm{\nu} \rightarrow \mathrm{^{7}Li} + \gamma \\
\mathrm{^{7}Li} & + \mathrm{p} \rightarrow \mathrm{^{4}He} + \mathrm{^{4}He} \\
\mathrm{^{8}B} & + \mathrm{p} \rightarrow \mathrm{^{8}Be} + \mathrm{e^{+}} + \mathrm{\nu} \\
\mathrm{^{8}Be} & + \mathrm{e^{-}} + \mathrm{\nu} \rightarrow \mathrm{^{8}B} + \gamma \\
\end{align*} \]
Elementary Nuclear Burning Cycles

- H Burning: CNO Cycle

\[ ^{13}\text{C} \rightarrow p, \gamma \rightarrow ^{14}\text{N} \rightarrow p, \alpha \rightarrow ^{17}\text{O} \rightarrow p, \gamma \rightarrow ^{18}\text{F} \]

\[ ^{12}\text{C} \rightarrow p, \alpha \rightarrow ^{15}\text{N} \rightarrow p, \gamma \rightarrow ^{16}\text{O} \rightarrow p, \gamma \rightarrow ^{18}\text{O} \rightarrow p, \gamma \rightarrow ^{19}\text{F} \rightarrow p, \gamma \rightarrow ^{20}\text{Ne} \]

Net Burning towards $^{14}\text{N}$

$^{12}\text{C}/^{13}\text{C} \sim 4$ (SAD:89)
Elementary Nuclear-Burning Cycles

• He Burning: 3α Cycle

\[
\begin{align*}
4\text{He} + 4\text{He} & \leftrightarrow 8\text{Be} \\
8\text{Be} + 4\text{He} & \leftrightarrow 12C^* \rightarrow 12C
\end{align*}
\]

- Lifetime \(^8\text{Be} \sim 7 \times 10^{-16} \text{ s}\)
- \(^8\text{Be}(\alpha,\gamma)_{12}\text{C}\) through Excited Level at 278 keV+ (Salpeter, Hoyle)
- \(\varepsilon \sim T_8^{40} \rightarrow \text{He Flash}\)
# Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Main Product</th>
<th>Secondary Products</th>
<th>Temp ($10^9$ K)</th>
<th>Time (yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>He</td>
<td>$^{14}$N</td>
<td>0.02</td>
<td>$10^7$</td>
</tr>
<tr>
<td>He</td>
<td>C, O</td>
<td>$^{18}$O, $^{22}$Ne and s-process</td>
<td>0.2</td>
<td>$10^6$</td>
</tr>
<tr>
<td>C</td>
<td>Ne, Mg</td>
<td>Na</td>
<td>0.8</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Ne</td>
<td>O, Mg</td>
<td>Al, P</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>O</td>
<td>Si, S</td>
<td>Cl, Ar, K, Ca</td>
<td>2.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Si</td>
<td>Fe</td>
<td>Ti, V, Cr, Mn, Co, Ni</td>
<td>3.5</td>
<td>1 week</td>
</tr>
</tbody>
</table>
Evolution of a Massive Star

Gravity <-> Nuclear Energy

When Fuel Exhausted ->
Contraction and Heating
(Except if Degenerate)
-> ... Fe Core
The advanced burning stages are characterized by multiple phases of core and shell burning. The nature and number of such phases varies with the mass of the star.

Each shell burning episode affects the distribution of entropy inside the helium core and the final state of the star (e.g., iron core mass) can be non-monotonic and, to some extent, chaotic.

Neutrino losses are higher and the central carbon abundance lower in stars of higher mass.
$^{26}$Al Nucleosynthesis: Example of a Cosmic Reaction Network, Common for Intermediate-Mass Isotopes
Si Burning: Quasi-Statistical Equilibrium
QSE Groups and their Links

\[ ^{45}\text{Sc}(p,\gamma)^{46}\text{Ti} \]

Arrows = Relative Effectiveness of Reaction Link

- Reaction Links Depend on Most Critically on \( Y_e \)

\text{Hix & Thielemann, ApJ 1996}
Massive Star Core Structure

(25 M_☉)

- **1H, 4He**
- **12C, 16O**
- **4He, 16O, 20Ne, 24Mg**
- **16O, 24Mg, 28Si**
- **28Si, 32S**
- **Si → Fe, Ni**

<table>
<thead>
<tr>
<th>∆m/M</th>
<th>9.9</th>
<th>9.5</th>
<th>8.9</th>
<th>8.7</th>
<th>8.3</th>
<th>7.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>envelope</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

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Core Collapse
Supernova Model
**Issues in CC-Supernova Models**

- Explosion Mechanism = Competition Between Infall and Neutrino Heating
- 3D-Effects Important for Energy Budget AND Nucleosynthesis
- Location of Ejecta/Remnant Separation
- $^{44}$Ti Produced at $r < 10^3$ km from $\alpha$-rich Freeze-Out, $\Rightarrow$ Unique Probe (+Ni Isotopes)
Accretion onto Compact Objects

- Angular Momentum of Matter Flow from Companion -> Accretion Disk
- Accretion Flow Dynamics -> Luminosity / Spectral “States”, Instabilities
- Radiation Sources:
  - Accretion Disk
  - Corona
  - Compact-Star Surface
- Scattering, Absorption

(Cyg X-1: Wilms et al., 1996; GRO J0422+32, GS2000+25: Sunyaev et al., 1993, Kroeger [priv. comm.])
What Makes a Supernovae Ia

Close Binary System

White Dwarf Merger

Central C Ignition

SN Ia Models

SN Ia

He Layer

He Shell Flash

WD

Giant

WD at \( M_{\odot} \)

C/O Layer

Binary Mass Transfer

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How Does a SNIa Explode?

- C Ignition at $M_{ch}$ Limit (possibly many ignition points)
- Turbulent Flame Propagation
- WD Expansion $\rightarrow$ Flame Extinction

- Issues: Rapid Time Scales!
  - Nuclear Burning $C+O \rightarrow ^{56}Ni$
  - Expansion
  - Mixing
Supernovae

- Explosion of a Star
- Nuclear Energy Release
  - Radioactive By-Products of Explosive Nucleosynthesis
  - Progressive Transparency of Exploding Star
  - Thermonuclear Supernovae (Type Ia)
  - Gravitational Collapse

![Graph showing light curves of different types of supernovae](SN_1987_A.png)

Days after maximum light vs. blue magnitude

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Element Distribution in a Young SNR

- X-Ray Emission Lines
  - Element Abundance & Spatial Distribution
  - Ionization Degree (Temperature & Density)

- Kepler, XMM/Newton:
  - SNR Cavity Hotter Inside
  - Fe and Si Distributions Similar
  - One-Sided CSM/ISM Interaction
Supernovae and Supernova Remnants

- **Prompt SN Light from Radioactivity**
- **SN Debris Reflects Nucleosynthesis (and Collapsing-Star Structure)**
- **Interaction of Blast Wave with ISM Results in Shocked Gas & Recombination Radiation**

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**Fig. 5.** Abundance maps for the elements included in the spectral fitting. All are plotted on the logarithmic scale indicated by the bar at the bottom.

**Fig. 2.** An example of a spectral fit within a single 20'' x 20'' pixel – cool component in blue, hot component in green and full model in red.
Hot Plasma

- \( T \gg 6000\text{K} \)
  - Matter Ionized: Ions and Electrons
  - Processes:
    - Coulomb Scatterings
    - Bremsstrahlung / Free-Free Radiation
    - Recombinations / Ionizations
    - Comptonization / Compton Scattering
  - Thermal and Non-Thermal Particle Populations
    (\( \rightarrow \) Radiation Components)
Accreting Neutron Stars: X-ray bursters

Neutron star (H and He burn into heavier elements)

Companion star (H + He envelope)

Accretion disk (H and He fall onto neutron star)

X-ray burst

"Superburst"

(4U 1735-44)
rp-Process: Impulsive H-Burning

- X-ray Burst Sources: Nuclear Flash of Accreted H Surface Layer of Neutron Star
- Nuclear Energy < Accretion Luminosity
- Type-I X-ray Burst Recurrence Periods ~h...d (Accretion of <10^{-8} \, M_\odot \, yr^{-1})
- rapid p Captures and \( \beta \)-Decays Dominate Nuclear Reactions (hot CNO, \ldots)
- rp Process Termination through SnSbTe Cycle
- Cosmic Source of Specific p-Isotopes \(^{92,94}\)Mo, \(^{96,98}\)Ru
- Ref.: Bildsten 2000, Schatz et al. 2001

**Ref.: Bildsten 2000, Schatz et al. 2001**
Atomic Nuclei: Stable and Radioactive

- Stable Isotopes
- n and p Evaporisation Limits (‘drip lines’)
- Regions of $\alpha$, $\beta^+$, $\beta^-$-Decaying Isotopes
**s-Process**

- **Successive $n$ Captures, Allowing Time for In-Between $\beta$ Decays**
- $n$ Densities $\sim 10^8$ cm$^{-3}$
- Populates Isotopes on the $n$-Rich Side Along the Valley of Stability
- Isotopes with a Stable $n$-richer Isobar are 's-Process-Only'-Produced (shielded)
- **Likely Site:**
  - Stellar Hydrostatic Burning (Shells in Giant Stages)

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**n Capture**

*abundance distribution with $A$: narrow s-process peak, broad r-process bump*

---

*Graph showing the abundance distribution with $A$: narrow s-process peak, broad r-process bump.*

---

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Production of Elements Beyond the Fe Peak: 
r-Process and s-Process

- Seed Nuclei (~ Fe-Group Elements) Capture Neutrons
- $\beta$ Decays Establish Final Abundances
  - $n$ capture faster than $\beta$-decay $\rightarrow$ r-process
  - $n$ capture slower than $\beta$-decay $\rightarrow$ s-process
**r-Process**

- **“Waiting-Point” Approximation:**
  - $r$-Process Path = Connection of Isotopes with Identical Neutron Separation Energy $S_n$
  - Constant Neutron Flux and Temperature over Exposure Time
  - Instantaneous Freeze-Out
  - Subsequent $\beta$-Decays

- **Phenomena & Results**
  - Abundance Peaks at $A=80, 130, 195$
  - $r$-Process Path $\sim 15-35$ Units from Valley of Stability
  - $S_n \sim 2-4$ MeV
  - $n_n \sim 10^{20}-10^{24}$ cm$^{-3}$, $T \sim 1.4 \times 10^9$K
  - $\tau \sim 10^{-4}...2$ sec

- **Unknowns:**
  - Astrophysical Site & Parameters
  - Nuclear Structure far off Stability

- **Two Independent $r$-Process Sites?**

- **Likely Sites:**
  - $\nu$ Wind from PNS in collapsing Fe Core of $cc$-SN
  - Explosive He Shell Nucleosynthesis ($^{13}C, ^{20}Ne$)

- **‘Shell-Quenching’ Models for Nucleus May Be Favored**
Elemental Abundances / Metal-Poor Stars

- Observations of Elemental Absorption Lines in Stellar Spectra
- Halo Stars:
  - Metal-Poor
  - Metals from Single Nucleosynthesis Event Nearby?
- Study Single-Event Synthesis of Elements > Fe (r,s-Process)

High-Energy Interactions of Cosmic Matter

- Relativistic Particles Interact with:
  - Electromagnetic Fields
    - Curvature Radiation
    - Synchrotron Radiation
    - Bremsstrahlung
    - Pair Creation
  - Particles, Atoms
    - Nuclear Excitation
    - Spallation
- **r process**
  - Mass known
  - Half-life known
  - Nothing known

- **s process**
- **p process**
- **rp process**

- **stellar burning**
- **Supernovae**
- **Cosmic Rays**
- **Big Bang**

- Elements:
  - Pb (82)
  - Sn (50)
  - Fe (26)
  - H(1)

- Processes:
  - **neutrons**
  - **protons**
Astronomical Instruments: Ground-Based

- NTT
- Effelsberg
- Arecibo
- VLT
- HEGRA

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Astronomical Instruments: HE Space Missions

ROSAT

CGRO

INTEGRAL

SWIFT

Chandra

BeppoSAX

XMM-Newton

RXTE
Cosmic Objects: Which Isotope Composition, Why?

- Galaxies
- Stars
- Interstellar Gas
**Massive-Star / ISM Interactions**

- Massive Stars Often Form in Groups
- Massive-Star Winds and SNaes Determine the ISM Morphology
- Massive-Stars' Metal-Enrichment of ISM Determines Chemical Evolution

- Evolution Time Scale of Stellar Groups: \(~10-100~\text{Myr}\)
- Evolution Time Scale of Massive Stars: \(~0.1-10~\text{Myr}\)
- Cosmic-Ray 'Propagation Age' \(~10~\text{Myr}\)

- Evolution of Stellar Populations
- Evolution of Diffuse Emission
- Issues in Massive-Star/ISM Interactions
  - ISM/Shock Interactions
  - Hot-Bubble Evolution
  - Matter Recycling
  - Star Formation History
  - ISM Morphology

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The Cosmic Cycling of Matter

dense molecular clouds

star formation (~3%)

SN explosion

stars

M~10^4-6 M☉

10^8 y

dense molecular clouds

interstellar medium

condensation

infall

mixing

Galactic halo

... galaxy collisions...

SNR's & hot bubbles

10^2-10^6 y

SN explosion

~90%

SNIa

compact remnant (WD, NS, BH)

SNIa

M > 0.08 M☉

10^6-10^10 y

winds

... galaxy collisions...
Abundances in Intergalactic Gas

• **X-Ray Spectroscopy (XMM/Newton, ZEUS)**
  - Study Composition of Inter-Cluster Gas
  - Large-Scale Transport of Nucleosynthesis Products
  - Nucleosynthesis Across the Universe

*Image: Chandra 3C295*
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