Origins II: Cosmology, stellar evolution and nucleosynthesis

Cosmic abundances, nucleosynthesis and origin of the elements

- The cosmic abundance of the elements
  - general patterns
- Creating the universe
  - Primordial nucleosynthesis
- The birth, life and death of a star
  - Origins and fusion modes
  - The end results
  - Nucleosynthesis

Cosmic abundance of the elements

Foundations

- The Four Forces
  - Strong nuclear Force
    - very short range, between nucleons, strength ~ 1
  - Electromagnetic Force
    - infinite range, but shielded, strength ~ 10^-2
  - Weak Nuclear Force
    - extremely short range, leptons, strength ~ 10^-13
  - Gravity
    - infinite range, no shielding, strength ~ 10^-39

Underlying Principles

- Quantum mechanics
  - wave-particle duality
  - isospin and fermion statistics
  - shell structure
- Relativity
  - space-time curvature and the expanding universe
  - mass-energy equivalence: $E = mc^2$

Controlling factors on nuclear stability

- Number nucleons
  - the more the merrier
- Spin pairing
  - favours even #s
- Shell structure
  - “magic numbers”
- Surface tension
  - like liquid drop
- Coulomb repulsion
  - limits ultimate size

All About Radioactive Decay

- Modes: Alpha, Beta*, Gamma, Fission
- Greater $\Delta E$ → Less stable → shorter $t_{1/2}$
- $dN/dt = -\lambda N \rightarrow N = N_0 e^{-\lambda t} \rightarrow t_{1/2} = (\ln 2)/\lambda$

- Dating types:
  - Simple Dating:
  - Parent-Daughter Dating:
  - Secular (Dis-)Equilibrium Dating:

*n*the elusive neutrino takes away ~ 1/3 the energy of a $\beta$ decay
And Decay Branching…

- $^{19}$K$^{40}$ is unstable, and decays either to
  - $^{20}$Ca$^{40}$ (by $\beta^-$ decay) 89% of the time, or
  - $^{18}$Ar$^{40}$ (by electron capture, $\beta^+$ decay) 11% of the time
- The composite decay rate is related to the sum of the probabilities, i.e.,
  
  \[ \lambda_{\text{tot}} = \lambda_1 + \lambda_2 \]
  
  \[ t_{\text{tot}} = \frac{1}{1/t_1 + 1/t_2} \]

* I forgot to mention this last lecture…

Let there be light...

- The universe was created in a big bang about $15 \times 10^9$ years ago:
  - a hot, infinitely dense singular point
  - expanded very rapidly
  - Protons & neutrons couldn’t exist for the first minute or two
  
  - Cosmic abundances, nucleosynthesis and origin of the elements
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And there was light...

Cosmic microwave background: echo of the big bang

All bodies emit a “black body radiation spectrum” whose amplitude and maximum wavelength related to temperature

- CMB is red-shifted to an incredibly low temperature
- Patches caused by inflation of quantum fluctuations

And there was motion...

Objects further away are receding more rapidly (velocity proportional to distance) means the universe is expanding…

- The HRS and CMB form 2 most convincing “proofs” of the Hot Big Bang

And then matter...

- The universe was created in a big bang about $\sim 13 \times 10^9$ years ago:
  - a hot, infinitely dense singular point
  - expanded very rapidly
  - light elements form
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Stellar Birth
- Some compression of the otherwise homogeneous gas cloud
  – collision of clouds
  – or a shock wave
- gravitational self attraction and collapse
  – accelerates with time
  – collapse ==> heating

Stellar Evolution:
- Gravitational heating
- Early high luminosity – effective cooling
- Deuterium burning – D rapidly exhausted
- Further collapse – intense heating – opacity increases
- Density reaches fusion threshold...

The onset of fusion:
- If gas is hot enough
  – nuclei moving fast enough to overcome mutual repulsion due to like (positive) nuclear charges
- and if gas is dense enough
  – many collisions per unit time to allow reactions to proceed
- then nuclei can begin to hit each other and "stick together" with strong nuclear force

Fusion Energy
- The whole is less than the sum of the parts
  – 4 of 1H weigh more than 4He
  \[ ^1H + ^1H \rightarrow ^2H + \beta^+ + \nu + \Delta E_1 \]
  \[ ^1H + ^3H \rightarrow ^4He + \gamma + \Delta E_2 \]
  \[ ^3He + ^3He \rightarrow ^4He + ^4He + \Delta E_3 \]
  – mass is energy!!

Mass \(^1H = 1.0078 \text{ amu} \) (x 4 = 4.0312 amu)
Mass \(^4He = 4.0026 \text{ amu} \)
Hydrogen “burning”

- The first/best viable energy source
- Rate ~ $T^{15}$
- lasts most of the star’s life (~ $10^{10}$ y)
- makes He from H
- eventually runs out…
  - the star begins to cool
  - … and starts to collapse further
  - … compression leads to additional heating

Fusion Energy

- Other ways to skin the cat, e.g., the CNO bi-cycle

\[
\begin{align*}
{}^{12}\text{C} + \text{H} & \rightarrow {}^{13}\text{N} + \gamma \\
{}^{13}\text{N} & \rightarrow {}^{13}\text{C} + e^+ + \nu \\
{}^{13}\text{C} + \text{H} & \rightarrow {}^{14}\text{N} + \gamma \\
{}^{14}\text{N} + \text{H} & \rightarrow {}^{15}\text{O} + \gamma \\
{}^{15}\text{O} & \rightarrow {}^{15}\text{N} + e^+ + \nu \\
{}^{15}\text{N} + \text{H} & \rightarrow {}^{16}\text{C} + {}^{4}\text{He}
\end{align*}
\]

- Uses C, N, & O as catalysts, so don’t need much
- Rate ~ $T^{20}$

Doing more of a good thing:

- Moving up the binding energy curve…
- combine He to make bigger nuclei
- actually difficult, because there’s no stable “mass 8” nucleus

Burning He

- Requires higher temperatures to overcome bigger charge barriers (He is 2+)
- Requires higher pressures to increase collision rates (half-life of intermediaries is $10^{-16}$ s)
  - takes place in stellar cores

\[
\begin{align*}
\frac{4}{2}\text{He} + \frac{4}{2}\text{He} & \rightarrow \frac{8}{2}\text{Be} + \gamma \rightarrow 2^{\frac{4}{2}}\text{He} \\
\frac{8}{4}\text{Be} + \frac{4}{2}\text{He} & \rightarrow \frac{16}{6}\text{C} + \gamma
\end{align*}
\]

- This is called “Helium Flashing” and is mostly done by “white dwarves”
- Requires higher pressures
  - takes place in stellar cores
  - is very exothermic

He Burning: climbing the “alpha ladder”

- The next rung: $^{12}\text{C} + {}^{4}\text{He} \rightarrow ^{16}\text{O} + \gamma$
- And so on:

\[
\begin{align*}
{}^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \\
{}^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne} \\
{}^{20}\text{Ne}(\alpha,\gamma)^{24}\text{Mg}
\end{align*}
\]

- A short-hand for the reactions

*Reaction rate is very sensitive to temperature and pressure
A star suddenly heats up due to the onset of He burning: expands, cools, and then extinguishes the He burning
Living in the balance: what makes the star “tick”

- The enemy:
  - relentless gravitational pull to implode
  - heat loss due to:
    - electromagnetic radiation (light) into space
    - neutrino losses from beta-decay (p => n)
- The tool:
  - use strong nuclear force to fuel fusion
  - heat produced from fusion:
    - creates heat and pressure to balance gravity

The beginning of the end...

- Running out of steam:
  - higher temperatures/pressures needed to burn
  - higher charge barriers
  - fewer gains for work done
  - lower slope on BE curve
  - eventually the slope turns over (becomes negative) so the reaction becomes “endothermic”, nuclei above maximum tend to fall apart

A stellar profile

- The star has an shell or onion-like character
  - with hotter shells near the core
  - cooler shells on the outside
  - H-burning on the outer shell
  - He, C, O, Si burning inward
- Its life is measured in years...
  - The e-process is fundamentally fruitless
    - neutrino losses are relentless
    - the star has nowhere to go...

Structure of an Evolved Massive Star

- Lifetime measured in seconds
  - inner core
    - turns endothermic
    - collapses
    - compresses to nuclear density (10^15g cc^-1)
    - becomes a giant nucleus
    - beta decays

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February 23, 1987
Bang!

You’re dead

- Lifetime measured in seconds
- inner core
  - turns endothermic
  - collapses
  - compresses to nuclear density ($10^{15} \text{ g cm}^{-3}$)
  - becomes a giant nucleus
  - beta decays

Neutrino shock wave blows off outer shell

SN1987A

Neutrinos from SN 1987A

- Energy output of supernova:
  - Core temperature $\sim 200 \times 10^9 \text{ K}$
  - Core collapse releases $10^{54} \text{ ergs}$ (gravitational)
  - 0.1% emerged as light
  - 1% as physical shock wave
  - $\sim 99\%$ lost by neutrinos
- on earth $\sim 5 \times 10^{10}$ neutrinos passed through each cm$^2$
  - 20 events seen $\sim 1$ day prior to arrival of light

Neutrinos from SN 1987A

- How do you “detect” a neutrino?
  - Have a very large target
  - Eliminate “non-events”
  - Be very very patient
  - E.g., Super-Kamiokande
    - Cherenkov radiation* detector
    - 50,000 tons ultrapure water (40 m diam., 40 m high)
    - 1000 m underground

Neutrinos and Super-K

*photonic “sonic boom”
Neutrinos in Super-K

And then in November, 2001…

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The final hours before nova

- Neutrons made during He and Si burning are boiled off during e-process defragmentation of Fe-type nuclei
  - called the "s-process"
  
  Neutron addition rate is slower than or comparable to decay rates of unstable nuclei near the "valley of stability"
  
  Nuclides follow the floor of the valley like a river
  
  Some isotopes not made this way

The final seconds of nova

- Neutrons boil off the collapsing core, streaming outward through the shell
  - at first "slowly"
  - then "rapidly"
  - called the "r-process"

  Neutron addition rate is much faster than decay rates of unstable nuclei near the "valley of stability"

  The valley is flooded!

The final milliseconds of nova

- The outbound stream of neutrons entrains protons and other nuclei
  - Leads to p-capture reactions
  - called the "p-process"

  Drives nucleosynthesis up the proton-rich side of the valley, e.g., making $^{136}$Ce and $^{144,148}$Sm isotopes

What happens next?

- What’s left behind depends on stellar mass
  - small initial mass → sputter to dwarfdom
  - medium mass → collapse to neutron star (pulsars)
    - $1.4 M_{\odot} < M < 3 M_{\odot}$
    - spin rate from $0.1 \, \text{s}^{-1}$ to $10,000 \, \text{s}^{-1}$
  - major league → collapse to black hole
    - $M > 3 M_{\odot}$
    - & @ galactic centers

- Gas and material ejected into large clouds that expand to seed new star formation
  - At speeds approaching $10,000 \, \text{km/s}$
  - shock wave compresses gases → new stars
  - second/third generation stars rework material
An example: the Crab Nebula

A supernova observed in 1054 AD leaves behind a cloud of gas and debris with an embedded neutron star/pulsar.

And the beat goes on...

26Al has a half-life of only 730,000 years (short compared to the universe). It must have been produced recently in nucleosynthetically active regions.

Our sun

- Our sun is a second generation star
  - the solar system formed from the ashes of a supernova
    - step 1: blow up a star, creating all of our elements
    - step 2: make a new solar system
  - How do we measure the timing of this?

Uranium Isotopes

- All Uranium isotopes are unstable, but two have very long half-lives:
  - 238U decays with a half-life of \(4.51 \times 10^9\) years
  - 235U decays with a half-life of \(7.10 \times 10^6\) years
- Present day ratio: \(\frac{^{235}U}{^{238}U} \approx 7 \times 10^{-5}\)
- The lighter isotope was more abundant during formation: \(\frac{^{235}U}{^{238}U} \approx 1.3\)

Uranium Isotopes

- The isotopes decay at unequal rates:
  - \(^{235}U = 235Ue^{-\lambda_{235}t}\)
  - \(^{238}U = 238Ue^{-\lambda_{238}t}\)
Uranium Isotopes

\[ ^{235}U = ^{235}U_0 e^{-\lambda_{235}t} \]

Given

\[ ^{238}U = ^{238}U_0 e^{-\lambda_{238}t} \]

We then have

\[ \frac{^{235}U}{^{238}U} = \frac{^{235}U_0 e^{-\lambda_{235}t}}{^{238}U_0 e^{-\lambda_{238}t}} = e^{-(\lambda_{235} - \lambda_{238})t} \]

or

\[ R = R_0 e^{-(\lambda_{235} - \lambda_{238})t} \]

or

\[ \frac{R}{R_0} = e^{-(\lambda_{235} - \lambda_{238})t} \]

\[ t = \frac{\ln \left( \frac{R}{R_0} \right)}{\lambda_{235} - \lambda_{238}} \]

\[ \ln \left( \frac{R}{R_0} \right) = -(\lambda_{235} - \lambda_{238})t \]

Taking natural log of both sides & substituting the numbers

\[ t = \frac{\ln \left( \frac{R}{R_0} \right)}{\lambda_{235} - \lambda_{238}} = \frac{\ln \left( \frac{0.0072}{1.3} \right)}{1.537 \times 10^{-10} - 9.763 \times 10^{-10}} \]

\[ t = 5.196 -8.226 \times 10^{-10} = 6.3 \pm 0.2 \text{Ga} \]

\[ \pm 0.2 \text{Ga due to 20% uncertainty in original ratio} \]

**232Th and 238U**

- A similar exercise:
  - \((232\text{Th}:238\text{U})_0 \approx 1.6 \pm 0.3\)
  - \(232\text{Th} \text{ half-life} = 14.1 \times 10^9 \text{y} \)
  - \(238\text{U} \text{ half-life} = 4.51 \times 10^9 \text{y} \)
  - \(238\text{U} \text{ decays faster than } 232\text{Th} \)
  - \((232\text{Th}:238\text{U})_{\text{present}} \approx 2.8 \pm 0.8\)

\[ \ln \left( \frac{R}{R_0} \right) = -(\lambda_{232} - \lambda_{238})t \]

\[ t = \frac{\ln \left( \frac{R}{R_0} \right)}{\lambda_{232} - \lambda_{238}} \]

\[ t = \frac{-0.5596}{-4.916 \times 10^{-10} - 1.5335 \times 10^{-10}} = -1.0419 \times 10^{-10} = 5.4 \text{Ga} \]

\[ \ln \left( \frac{R}{R_0} \right) = -(\lambda_{232} - \lambda_{238})t \]

\[ t = \frac{\ln \left( \frac{0.0072}{1.3} \right)}{1.537 \times 10^{-10} - 9.763 \times 10^{-10}} \]

\[ t = 5.196 -8.226 \times 10^{-10} = 6.3 \pm 0.2 \text{Ga} \]

\[ \pm 0.2 \text{Ga due to 20% uncertainty in original ratio} \]

**232Th vs. 238U**

- Is 5.4 Ga different from 6.3 Ga?
  - (and whom do you believe?)
  - If you vary the primordial ratios by \(\pm 20\%\) (a reasonable uncertainty) you get:
    - \((232\text{U}:238\text{U}) = 6.1 - 6.5 \text{ Ga} \)
    - \((232\text{Th}:238\text{U}) = 3.5 - 7.2 \text{ Ga} \)
  - The better estimate for former is due to \(235\text{U}\)'s short half-life
  - Also, there are many processes in nature (i.e. during the formation of the earth and subsequent reprocessing) that can affect Th/U ratios

**But wait… it’s more complicated than this!**

- If nucleosynthesis is occurring continuously
  - Nuclear "inventories" will grow until decay balances production
  - For U isotopes we have

\[ \frac{P_{235}}{P_{238}} = \frac{\lambda_{233} N_{235}}{\lambda_{238} N_{238}} \]

which gives

\[ \frac{N_{235}}{N_{238}}_{\text{Initial}} \]

\[ \ln \left( \frac{R}{R_0} \right) = -(\lambda_{235} - \lambda_{238})t \]

\[ t = \frac{\ln \left( \frac{R}{R_0} \right)}{\lambda_{235} - \lambda_{238}} \]

\[ t = \frac{\ln \left( \frac{0.0072}{1.3} \right)}{1.537 \times 10^{-10} - 9.763 \times 10^{-10}} = -5.324 -8.226 \times 10^{-10} = 4.04 \text{Ga} \]

**But wait… it’s more complicated than this!**

- But it takes multiple half-lives to reach "secular equilibrium"
  - \(235\text{U}\) will reach this value before \(238\text{U}\)
  - And much sooner than \(232\text{Th}\)
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• The timing of it all…