Abundance of Elements

<u>Outline</u>:
1) What is the universe made of?
2) How do we know what the universe is made of?
3) Where do the elements come from?
    - Nuclear fusion
    - Neutron capture
4) Open questions / research areas

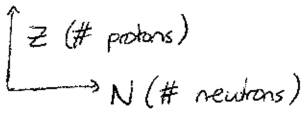
1) What is the universe made of?

ignore dark energy (~70%), dark non-baryonic matter (~26%)

Most of baryonic matter is hydrogen (~75% of $m_{baryonic}$), followed by helium (~20-25%)
- only trace amounts of other elements — "metals"
- Solar system abundance curve (slide 1)

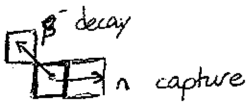
features:
- Fe peak
- more even-Z elements b/c of α enhancement
- dip at Li, Be, B

Table of nuclides (slide 2) is the periodic table for astronomers



⟹ different nuclear reactions can take you to different isotopes on the table

ex)



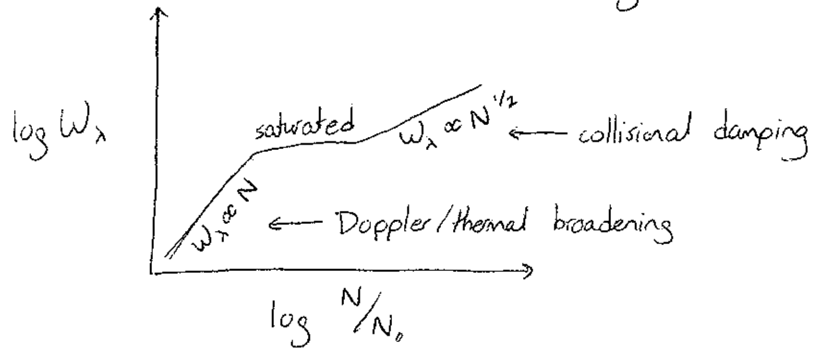
2) How do we know what the universe is made of?

Geology: chemical analysis / mass spectroscopy of Earth, Moon, meteorites

Astronomy: <u>spectroscopy</u>!

Brief review of (absorption) spectroscopy:

- Take spectrum
- Measure equivalent width (EW or W_λ) of absorption line
- Convert to abundance with curve of growth model



The curve of growth is at some fixed T, P

- Can do absorption spectroscopy for the Sun + other stars
  - Cecilia Payne-Gaposchkin (1925) — 1st evidence that universe mostly hydrogen (based on stellar spectra)
- Can also do absorption/emission line spectroscopy for ISM, but this is usually more complicated because gas not necessarily in thermodynamic equilibrium

(Even though chemical abundances vary from place to place, it is still useful to envision a "cosmic abundance distribution".)

3) Where do the elements come from?

Big Bang Nucleosynthesis: H, He, trace amounts of Li (+ deuterium)

Stars make the rest!

① Fusion of light elements — BE/nucleon curve (slide 3)

- H → He: pp-chain, CNO cycle
  ↳ check out Fe[26] game
- He → C: triple-α process
- C → O: $^{12}C + \alpha \longrightarrow {}^{16}O$

⟹ any questions? good time to review

- Fusion past C, O? depends on <u>degeneracy</u> of the core
  - recall:
  - — in degenerate core, P is independent of T (if T ⇑, core won't expand)
  - — core isothermal b/c e^- highly conductive
  - ⇒ if core ignites due to temp increase, it will ignite all at once!
    - → <u>explosive</u> event

ex) He ignition in low-mass ($< 2 M_\odot$) stars — "He flash"

C ignition in white dwarfs — "C flash"/"C detonation"

So have to distinguish between hydrostatic + explosive burning

↳ (v effective at explaining high-mass nuclei)

In the most massive stars ($M > 10 M_\odot$), get burning in non-degenerate environment:

- C burning : $^{12}C + {}^{12}C \rightarrow {}^{23}Na, {}^{20}Ne$, other stuff @ $T \sim 8 \times 10^8$ K
- O burning : $^{16}O + {}^{16}O \rightarrow {}^{31}P, {}^{28}Si$, other stuff @ $T \gtrsim 10^9$ K

These reactions are faster + more effective at producing heavy nuclei than α capture is.

- When you approach the Fe peak: <u>nuclear statistical equilibrium</u> (NSE)

At $T > 3 \times 10^9$ K, photons have MeV energies.

This is enough to photodissociate nuclei!

Nuclear reactions can reach equilibrium (similar to Saha [ionization equilibrium] or Boltzmann [e^- distribution eqm])

$$i + j \rightleftharpoons ij$$

$$\frac{n_i n_j}{n_{ij}} \sim T^{3/2} e^{-Q/k_B T}$$

↳ difference in BE between ij and (i+j)

⇒ Individual reaction rates don't matter — abundances depend only on T, ρ/entropy, + how neutron-rich the material is (+ difference in BE)

↳ parameterized as electron fraction

$$Y_e = \frac{n_e}{n_n + n_p}$$

So in NSE, the question is:

For a given T, what is the distribution of nuclei?

2 examples:

1) Si burning ($T \sim 5 \times 10^9$ K) — quasi-equilibrium state
($t_{equil} \sim 10^{-5}$ s $\Leftarrow$ things equilibrate quickly!)

After C+O burning, main nuclei left are ^{28}Si and ^{32}S
(less tightly bound)

^{28}Si photodisintegrates, liberating lots of light particles

ex) $^{28}Si(\gamma, \alpha)^{24}Mg$

Free particles then combine w/ heavier nuclei to make even heavier stuff

2) e^- process / neutronization (close to Fe peak)

BE/nucleon curve flattens at Fe peak, so NSE depends only on

temp, entropy, $\underline{\underline{Y_e}}$ — can predict abundances of Fe-peak v accurately!

⇓

note: higher density ρ = lower entropy per amt of energy deposited
= not as many light particles

(Things just go to lowest energy state!)

⇒ How to make elements heavier than Fe, where fusion is endothermic?

② Neutron capture: $n + {}^{N}X \longrightarrow {}^{N+1}X$

Neutrons don't have to overcome the Coulomb barrier, so reactions are different than fusion reactions (see "Nuclear reactions" lecture)

a) Where do neutrons come from? (Source of neutrons)

Free neutrons are rare (half life $\tau \sim 10$ min)

- so abundances of $A > 56$ elements are small
($\sim 10^{-10}$ of H, 10^{-5} of Fe)

Get neutrons from shell burning of lighter elements

ex) $^{12}C(p,\gamma)^{13}N(e^+,\nu_e)^{13}C(\alpha,\boxed{n})^{16}O$

$^{14}N(\alpha,\gamma)^{18}F(e^+,\nu_e)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,\boxed{n})^{25}Mg$

$\Rightarrow$ This is effective in 2-6 $M_\odot$ AGB stars (stars past He burning) + in SNe

b) How many neutrons are needed? (Flux of neutrons)

$$^{A}Z + n \longrightarrow {}^{A+1}Z$$

slow neutron ~~flux~~ capture = <u>s-process</u>: $^{A+1}Z \rightarrow {}^{A+1}(Z+1) + e^- + \bar{\nu}_e$

- can't capture many n's before β-decaying
- makes stable, mildly n-rich isotopes
- occurs in: AGB stars, ~~rotating~~ probably the most massive ~~stars~~ ones

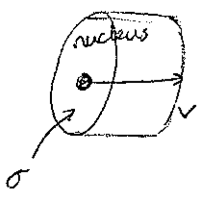
rapid neutron ~~flux~~ capture = <u>r-process</u>: $^{A+1}Z \rightarrow {}^{A+2}Z$

- capture many n's before β-decaying
- makes very neutron rich isotopes
- occurs in: ~~NSM~~ neutron star mergers (NSMs)? SNe?

s- and r-process elements on table of nuclides

(in-class activity, slide 5)

Let's do some physics to figure out the neutron densities needed for s- and r-process:



~~neutron~~ nucleus "carves out" volume per unit time σv:

$$\langle \sigma v \rangle = \int \sigma v \underbrace{\phi(v)}_{\text{velocity distribution}} dv$$

$$\approx \langle \sigma \rangle v_{th} \quad \text{where } v_{th} = \left(\frac{2k_B T}{m}\right)^{1/2}$$

is the thermal velocity

Note that $\sigma \propto v^{-1}$ because lower velocity means neutrons spend more time near nucleus

(don't have to worry about Coulomb repulsion)

Rate of neutron capture: $n_n \langle \sigma v \rangle$

$\quad$ ↳ neutron # density

Timescale for n capture: $\tau_n = \dfrac{1}{n_n \langle \sigma v \rangle}$

$\Rightarrow \langle \sigma \rangle \sim 0.1$ barn at $v_{th} \sim 3 \times 10^5$ cm/s

↳ large compared to charged particles

$$\Rightarrow \tau_n \sim \frac{10^9 \text{ yr}}{n_n}$$

s-process takes $\sim 10^4$ yr in AGB stars $\Rightarrow n_n \sim 10^5 \text{ cm}^{-3}$

r-process takes $\sim 10^{-6}$ s to avoid β-decay $\Rightarrow n_n \sim 10^{23} \text{ cm}^{-3}$

⟹ Most $A > 56$ stable isotopes can be produced with a combination of s- and r-processes, but some are especially "s" or "r" process

ex) mostly s → Ba, almost entirely r → Eu

$$\frac{\text{Ba}}{\text{Eu}} = \begin{cases} 10 & \text{for pure r-process} \\ 45 & \text{for Sun} \\ 500 & \text{for pure s-process} \end{cases}$$

Abundance patterns of n-capture elements: (slide 6)

3 main peaks

- s-process peaks occur at "magic numbers" in # of neutrons N (equiv. to filled shells of electrons — have lower n-capture cross sections)
- when this happens with r-process, get to magic numbers at lower mass numbers b/c isotopes are more neutron-rich

4) Open questions / research areas

- How do elements populate the universe over time?
  - initially, just have H, He, Li from Big Bang
  - then stars make stuff (← Pop III stars still a mystery)
  - Type II SNe go off first — make lots of α elements, Fe
  - Type Ia SNe go off after some delay — make Fe-peak elements but NOT α elements

show [α/Fe] vs [Fe/H] plot (slide 7)

- What is the dominant source of r-process elements?
  - NSMs — what better way to get high neutron fluxes than to smash 2 balls of neutrons together?
    - some evidence from single data point (GW170817)
      - ↳ optical transient dimmed + reddened over time, matching models of radioactive decay of r-process elements
    - but: Where do early r-process elements come from? Also, r-process enrichment seems to flatten out in places like the MW disk, where we expect NSMs to occur?
  - GRBs / SNe — might solve early r-process problem
    - but: Have to do complicated ν-heating physics to get a high enough neutron fraction (= low enough Y_e)?
- Other nucleosynthetic processes?
  - <u>p-process</u> = proton capture — occurs in SNe shocks
  - <u>i-process</u> = intermediate (b/w r- and s-process) — might occur in massive AGB *s
  - 2nd + 3rd r-process abundance peaks seem to be produced entirely by purely r-process, while 1st peak is different?
    - ⇒ "weak" r-process — maybe occurs in some NSM wind / accretion disk models?
- Abundances as a probe for other physics
  - Big Bang nucleosynthesis: abundances of lithium, deuterium can be used to probe cosmological parameters, like cosmic baryon density
  - stellar / supernova nucleosynthesis:
    - use r-process elements to independently constrain rate of NSMs (G. Duggan)
    - use abundances of elements produced by Type Ia SNe as probes of Type Ia physics
      - ex: Mn as a tracer of WD density! (M. de los Reyes)
        - show some ~~examples~~ plots from my research (slide 9)