Astro 507
Lecture 26
April 1, 2020

Announcements:

- **Preflight 5: due Friday**
  Office Hours: by email or appointment, or
  Instructor–after class today
  TA: noon-1pm tomorrow

Last time: big-bang nucleosynthesis (BBN) theory

- at $T \gg 1$ MeV: baryons are n and p
  Q: why don't the free neutrons decay?
  Q: what sets n/p? why is this ratio important?
- at $T \sim 1$ MeV: weak freezeout
  Q: what does this mean? why important?
- *Q: first reaction in buildup of nuclei?*
  Q: main products of BBN? why not $\rightarrow$ ^{56}Fe?

Reaction flows: tightest binding favored

$\rightarrow$ essentially all pathways flow to ^{4}He

`www: nuke network`

almost all $n \rightarrow {}^4$He:

$n(^4\mathrm{He})_{\mathrm{after}} = 1/2\ n(n)_{\mathrm{before}}$

$$Y_p = \frac{\rho(^4\mathrm{He})}{\rho_B} \simeq 2(X_n)_{\mathrm{before}} \simeq 0.24 \tag{1}$$

$\Rightarrow \sim 1/4$ of baryons into ^{4}He, $3/4\ p \rightarrow$H

result weakly (log) dependent on η

Robust prediction: large universal ^{4}He *abundance*

But $n \rightarrow {}^4$He incomplete: as nuke rxns freeze,
leave traces of:

- D
- ^{3}He (and ^{3}H$\rightarrow{}^3$He)
- ^{7}Li (and ^{7}Be$\rightarrow{}^7$Li)

abundances $\leftrightarrow$ nuke freeze T
trace species D, ^{3}He, ^{7}Li: strong $n_B \propto \eta$ dependence

BBN theory predictions summarized in **“Schramm Plot”**

Lite Elt Abundances vs η

www: Schramm plot

Note: no $A > 7$...so no C,O,Fe... *Q: why not?*

Why no elements $A > 7$?

1. *Coulomb barrier*
heavier products require heavier reactants
which have higher charges

2. nuclear physics: "mass gaps"
no stable nuclei have masses $A = 5, 8$
$\rightarrow$ with just p & ^{4}He, can't overcome via 2-body rxs
need 3-body rxns (e.g., $3\alpha \rightarrow {}^{12}$C) to jump gaps
but ρ, T too low

Stars *do* jump this gap, but only because have higher density a
long time compared to BBN

Testing BBN: Warmup

BBN Predictions: Lite Elements vs η

To test: measure abundances

Where and when do BBN abundances (Schramm plot) apply?

Look around the room–not 76% H, 24% He.
Is this a problem? Why not?

Solar system has metals not predicted by BBN
Is this a problem? Why not?

So how test BBN? What is the key issue?

When does first non-BBN processing start?

Testing BBN: Light Elements Observed

Prediction:

BBN Theory → light elements at $t \sim 3$ min, $z \sim 10^9$

Problem:

observe light elements in astrophysical settings

typically $t \gtrsim 1$ Gyr, $z \lesssim few$

stellar processing alters abundances

Q: If measure abundances in a real astrophysical system, can you unambiguously tell that stars have polluted?

Q: How can we minimize (and measure) pollution level?

stars not only alter light elements
    but also make heavy element = “metals”
    stellar cycling: metals ↔ time

Solution:
→ measure light elements and metals
low metallicity → more primitive
in limit of metals → 0: primordial abundances!

look for regions with low metallicity → less processing

Deuterium

Two methods:

(1) use D/H$_\odot$, model $D - Z$ evolution:
model dependent ✗ (old school)

(2) measure D/H at high z **YES**
"quasar absorption line systems"

QSO: for our purposes
high-z continuum source (lightbulb)

`www: QSO spectrum`

consider cloud, mostly H

- at $z < z_{\text{qso}}$, but still high z
  - e.g., $z_{\text{qso}} = 3.4, z_{\text{cloud}} = 3$
- H absorbs γ if energy tuned to levels
  - lowest: $n = 1 \rightarrow 2$, Lyα
- but Lyα in QSO frame
  - redshifted in cloud frame

What happens?

What about a cloud at yet lower z?

intervening material seen via absorption

H: “Lyman-α forest”

Deuterium in High-z Absorption Systems

D energy levels $\neq$ H: for Hydrogen-like atoms

$$E_n = -\frac{1}{n^2}\,\frac{1}{2}\,\alpha^2 \mu c^2 \qquad (2)$$

where μ = **reduced mass** $= m_e m_A/(m_e+m_A) \simeq m_e(1-m_e/A m_p)$

$\Rightarrow \Delta E = E_{n,D} - E_{n,H} \approx +1/2\ m_e/m_p\ E_{n,H}$

$\Rightarrow \Delta z_D = \Delta\lambda/\lambda = -1/2\ m_e/m_p$

$c\Delta z_D = -82$ km/s (blueward) → look for "thumbprint"

`www:  O'Meara D spectrum`

What about stellar processing?

★ stars *destroy* D *before* H-burning! (pre-MS)

★ nonstellar astrophysical (Galactic) sources negligible

Epstein, Lattimer & Schramm 1977; updated in Prodanović & BDF 03)

$\Rightarrow$ **BBN is only important D nucleosynthesis source**

$\rightarrow$ $D(t)$ only *decreases*

chem evol models: versus Z metallicity: $D \sim e^{-Z/Z_\odot} D_p$

Quasar absorbers: $Z \sim 10^{-2} Z_\odot$ → expect $D_{\rm QSOALS} \approx D_p$

Deuterium Results

Until recently: the 7 best systems
(clean D, well-determined H)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.78 \pm 0.29) \times 10^{-5} \tag{3}$$

Cooke, Pettini (2012, 2013): new very high-precision systems
Damped Lyα absorbers (DLAs):

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.53 \pm 0.04) \times 10^{-5} \tag{4}$$

now a 2% measurement!