Astro 596/496 PC
Lecture 23
March 12, 2010

Announcements:

- PF4 was due at noon
- PS4 out, due next Friday in class

Last time: began big bang nuke & particle cosmology

Big Bang Nucleosynthesis (BBN) expectations:

- BBN–CMB analogy: *unbound components* $\rightarrow$ *bound states*
- BBN epoch set by $T_{\text{BBN}} \sim B_{\text{nuke}} \sim 1$ MeV
  when $t(1\text{MeV}) \sim 1$ sec
- BBN occurs deep into radiation-dominated Universe

Element Synthesis

first step in building complex nuclei: $n + p \rightarrow d + \gamma$
but $d + \gamma \rightarrow n + p$ until $T \ll B(d)$; see Extras

when photodissocation ineffective, $n + p \rightarrow d + \gamma$ fast
rapidly consumes all free n and builds d
which can be further processed to mass-3:

$$d + p \rightarrow {}^3\mathrm{He} + \gamma \quad d + d \rightarrow {}^3\mathrm{H} + p \quad d + d \rightarrow {}^3\mathrm{He} + n \tag{1}$$

and to ^{4}He

$${}^3\mathrm{H} + d \rightarrow {}^4\mathrm{He} + n \quad {}^3\mathrm{He} + d \rightarrow {}^4\mathrm{He} + p \tag{2}$$

some of which can then make mass-7:

$${}^3\mathrm{H} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Li} + \gamma \quad {}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma \tag{3}$$

Q: what limits how long these reactions can occur?
Q: which determines which products are most abundant?

BBN Reaction Flows

Binding Energy

nuclei are bound quantum structures, confined by nuclear forces among the "nucleons" n, p

can quantify degree of stability–i.e., resistance to destruction via binding energy: for nucleus with Z protons, N neutrons, $A = N + Z$ nucleons

$$\begin{aligned} B_A &= \text{energy of individual parts} - \text{energy of bound whole} \\ &= (Z m_p + N m_n - m_A) c^2 \\ &> 0 \quad \text{if bound} \end{aligned}$$

note: generally B_A increases with A

but that's not the whole story on stability

binding shared among all A nucleons,
so binding per nucleon is B_A/A

nuclear stability ↔ high B_A/A

`www: plot of` B_A/A `vs` A
lowest binding/nucleon: d!
highest: ^{56}Fe, but among light elements, ^{4}He highest by far
Q: implications for BBN

Reaction flows: tightest binding favored

→ essentially all pathways flow to ^{4}He

`www: nuke network`

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

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

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

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

result weakly (log) dependent on η

Robust prediction: large universal ^{4}He abundance

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

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

abundances $\leftrightarrow$ nuke freeze T
trace species D, ${}^3\mathrm{He}$, ${}^7\mathrm{Li}$: 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

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: Lite Elements Observed

Prediction:

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

Problem:

observe lite 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 lite elts 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 **X** (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

$$E_n = -\frac{1}{n^2}\,\frac{1}{2}\,\alpha^2 \mu c^2 \tag{5}$$

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**

→ $D(t)$ 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 $D_{\mathrm{QSOALS}} \approx D_p$

Deuterium Results

For the 5 best systems
(clean D, well-determined H)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.78 \pm 0.29) \times 10^{-5} \tag{6}$$

For the top 2 (multiple transitions)

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.49 \pm 0.18) \times 10^{-5} \tag{7}$$

significant scatter in high-z D/H:
unknown systematics?
Sloan Survey → many QSO's → tighter D/H
very promising cosmological probe!

Assessing BBN: Theory vs Observations

(Standard) BBN theory has a free parameter: $n_B/n_\gamma = \eta$
different lite element predictions for different η
Q: so how to compare with observations?
is it even possible to test the theory?

What uncertainties are there in the standard *theory?*

What uncertainties are there in the obs?

How can we account for these uncertainties when comparing theory and observations?

If theory & obs agree, *what would this mean:*
qualitatively? quantitatively?
If they disagree, *what would this mean?*

Assessing BBN: Theory vs Observations

BBN Theory:

all elements dependent on η

the only free parameter in standard ("vanilla") calculation

$\Rightarrow$ for each η value, 4 lite elements: "overconstrained"

a priori η is unknown, but homogeneous U → one value today

`www: Schramm plot`

Lite Elt Observations:

1. measure *one* element: find η
2. measure *more* elements: each picks an η

   $\Rightarrow$ do they agree? test of BBN & of cosmology!

Assessing BBN: Procedure

Combine observations (+ errors!)
statistical errors only:
- ^{4}He and D agree
- ^{7}Li likes lower η

include systematics:

Concordance!

`www: Schramm plot w/ data boxes`

lite elts fit if η in range

$$3.4 \times 10^{-10} \leq \eta \leq 6.9 \times 10^{-10} \tag{8}$$

Have extrapolated hot big bang to $t \sim 1$ s
predict lite elts → agrees w/ theory
big bang model works back to $t \sim 1$ s, $z \sim 10^{10}$!

lends confidence to extrapolation $t < 1$ s

Directors’ Cut Extras

The Short but Interesting Life of a Neutron

(1) at $T > T_f$, $t \sim 1$ s
$n \leftrightarrow p$ rapid
maintain $n/p = e^{-\Delta m/T}$

(2) at $T = T_f$,
fix $n/p = e^{-\Delta m/T_f} \simeq 1/6$
so n "mass fraction" is

$$X_n = \frac{\rho_n}{\rho_B} = \frac{m_n n}{m_n n + m_p p} \approx \frac{n}{n+p} \approx 1/7 \tag{9}$$

(3) until nuclei form,
free n decay: $\dot{n} = -n/\tau_n$, with $\tau_n = 885.7 \pm 0.8$ s
then mass fraction drops as

$$X_n = X_{n,i} e^{-\Delta t/\tau} \tag{10}$$

Q: why take this simple from?

Nuclear Astrophysics: Overcoming the Coulomb Barrier

to go from n, p to ^{4}He requires
at least one nuclear reactions between charged nuclei
so must contend with Coulomb repulsion

$$V_C(r) = \frac{Z_1 Z_2 e^2}{r} \sim 1 \ Z_1 Z_2 \ \text{MeV} \ \left(\frac{1 \ \text{fm}}{r}\right) \tag{11}$$

but nuclear force, while strong, is short-ranged: $r_{\text{nuke}} \sim 1$ fm
$\rightarrow$ particles apparently need $mv^2/2 \sim |V_C| \sim 1$ MeV to fuse
but $mv^2/2 \sim T \ll 1$ MeV, and higher energies exponentially suppressed

Q: how can we overcome this barrier?

Quantum Mechanics to the Rescue

Quantum mechanics → tunneling
Penetration probability

$$P \propto e^{-2\pi Z_1 Z_2 e^2/\hbar v} = e^{-bE^{-1/2}} \tag{12}$$

so $P \neq 0$ even when $E \ll |V_C|$
→ tunnel under barrier, then react
note: not as serious an issue in BBN as it is in most stars
e.g., the sun