Astro 596/496 NPA
Lecture 19
March 1, 2019

Announcements:

- **Problem Set 3** due this afternoon
- **Preflight 4** due next Friday
- Program Note: rest for the weary!
  no class meeting next **Monday March 4**
  no class meeting Wed March 13 and Fri March 15
  and *so no assignment due Friday before Spring Break!*

Last time: finished BBN theory
Q: what are the main results?
how are these usually presented?

BBN theory: main result

- light element abundance predictions
- depend on baryon density $\leftrightarrow \eta \leftrightarrow \rho_{\text{baryon}}$

"Schramm Plot' '

Lite Elt Abundances vs η

summarizes BBN theory predictions

`www: Schramm plot`

Note: no $A > 7$... *Q: why not?*

Why don't we go all the way to ^{56}Fe*?*

after all: most tightly bound

$\Rightarrow$ most favored by nuke stat equil

Why no elements $A > 7$?

1. mass gaps at $A = 5, 8$
   Fermi, Turkevich $\sim$ 1950

2. Coulomb barrier

need 3-body rxns (e.g., $3\alpha \rightarrow {}^{12}$C) to jump gaps
but ρ, T too low

will see: 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 $\rightarrow$ 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 test for stellar pollution?

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

Metallicity Probes Pollution

stars not only alter light elements

but also make heavy element = “metals”

stellar cycling: metals $\leftrightarrow$ time

Solution:

$\longrightarrow$ measure lite elts and metals

low metallicity $\longrightarrow$ more primitive

in limit of metals $\rightarrow$ 0: primordial abundances!

look for regions with low metallicity $\longrightarrow$ less processing

Deuterium

Two methods:

(1) use solar $(\mathrm{D/H})_{\odot}$, model Milky Way $D - Z$ 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 *intergalactic cloud ("protogalaxy")*
mostly made of *hydrogen H*

- put cloud 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

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

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

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

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

$c\Delta z_D = -82$ km/s (blueward) $\rightarrow$ 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: $Z \sim 10^{-2} Z_\odot$ $\rightarrow$ expect $D_{\rm QSOALS} \approx D_p$

Deuterium Results

a challenge to find good systems
with ordinary H line width < 82 km/s

state of the art:

- **10 good systems** (clean D, well-determined H)
- metallicity (Si, Fe) $Z_{\text{absorber}} \sim (0.001 - 0.03) Z_{\odot}$: primitive!
- redshifts $z \sim 3$

abundance mean

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.569 \pm 0.027) \times 10^{-5} \qquad (2)$$

now a 1% measurement!!!

no correlation with redshift or metallicity $\rightarrow$ **primordial!**

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 $\rightarrow$ 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:

disagreement softened, but still present

- Concordance to within factor ~ 2 in η!

`www: Schramm plot w/ data boxes`

most constraining: deuterium

use this to find η

BBN Measurement of Cosmic Baryons

light element fit if η in range

$$5.8 \times 10^{-10} \leq \eta \leq 6.6 \times 10^{-10} \quad (3)$$

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

lends confidence to extrapolation $t < 1$ s

Director's Cut Extras

Helium-4

He atoms: high ionization potential
$\Rightarrow$ need hot H II region

hot, low metals $\rightarrow$ "extragalactic H II region"
metal-poor, dwarf irregular galaxies
`www: I Zwicky 18`

measure He lines in nebular spectra
Q: what kind of spectrum expected?
`www: He lines in I Zw 18`

data show: Y and Z *correlated*
What correlation do you expect?

Helium-4 Data: Trends and Implications

Data best fit by

$$Y = Y(Z) \simeq Y_0 + \frac{\Delta Y}{\Delta Z} Z \tag{4}$$

slope $\Delta Y/\Delta Z$: stellar nuke ("helium output per metal")
intercept $Y_0 = Y_p$: cosmology (primordial He!)

current world average (Olive & Skillman 2005):

$$Y_p = 0.249 \pm 0.009 \tag{5}$$

error budget is key, dominated by systematic effects
$\Rightarrow$ uncertain models of H II regions
$\Rightarrow$ line strength $\leftrightarrow$ abun. conversion

Note: use data itself to get $Y - Z$ evolution
"model-indep"

Helium-3

measure in ISM (H II regions)
via hyperfine emission ("21 cm")
spin-spin coupling $E_{\text{hf}} \propto S_e \cdot S_A$

good news:
since $S(^4\text{He}) = 0$, $S(^3\text{He}) = 1/2$,
only ^{3}He has signal: no ^{4}He "noise"!

`www: Rood et al` ^{3}He

bad news:
(1) ^{3}He only available at high metallicities
(2) (low mass) stellar nuke uncertain:
are stars net ^{3}He producers or destroyers?

Q: how to proceed?

Give up! ...for now, anyway

Do not use ^{3}He for BBN testing

but can turn problem around:
BBN predicts primordial ^{3}He
$\longrightarrow$ infer sign of, and degree of,
Galactic ^{3}He processing