Astro 596/496 NPA

Lecture 17

Oct. 2, 2009

Announcements:

- Preflight 3 due
- Problem Set 3 out, due next Friday

PF3: *what happens in a Universe where* $m_p - m_n = 1.29$ MeV*?*

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 $\leftrightarrow \eta \leftrightarrow \Omega_{\text{baryon}}$

"Schramm Plot' '

Lite Elt Abundances vs $\eta$

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 $\rho$, $T$ too low

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

## BBN History: The Standard Model Emerges

Peebles (1966):
numerical calculation of light elements

Wagoner, Fowler, & Hoyle (1967):
numerical calculation of light elements
extensive nuclear network, detailed thermodynamics
basic results & code (Wagoner 1973) same as today

# Testing BBN: Warmup

BBN Predictions: Lite Elements vs $\eta$

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 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 $\leftrightarrow$ 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

# Helium-4

He atoms: high ionization potential
⇒ need hot H II region

hot, low metals → "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?*

∞

**Transp:** $Y$ *vs* $Z$
*Q: significance of features?*

# Helium-4 Data: Trends and Implications

Data best fit by

$$Y = Y(Z) \simeq Y_0 + \frac{\Delta Y}{\Delta Z} Z \tag{1}$$

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):

$$Y_p = 0.249 \pm 0.009 \tag{2}$$

error budget is key, dominated by systematic effects
⇒ uncertain models of H II regions
⇒ line strength ↔ abun. conversion



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

# 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 $\gamma$ if energy tuned to levels
  lowest: $n = 1 \rightarrow 2$, Ly$\alpha$
- but Ly$\alpha$ in QSO frame
  redshifted in cloud frame

*What happens?*

*What about a cloud at yet lower $z$?*

intervening material seen via absorption

H: "Lyman-$\alpha$ forest"

# Deuterium in High-$z$ Absorption Systems

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

$$E_n = -\frac{1}{n^2}\,\frac{1}{2}\,\alpha^2 \mu c^2 \tag{3}$$

where $\mu$ = **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

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

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_p = (2.78 \pm 0.29) \times 10^{-5} \quad (4)$$

For the top 2 (multiple transitions)

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

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