Astro 507

Lecture 24

March 17, 2014

Announcements:

- **PS4: due Friday or upload by next Monday**
- Office Hours: Thurs. 3:10-4pm or by appt

Last time: light elements are born!

Q: why mostly ^{4}He*? why so insensitive to* $\eta \propto \Omega_{\rm baryon} h^2$*?*

Q: why is D/H tiny? why so sensitive to η*?*

why decreasing with η*?*

Q: why is ^{7}Li*/H really really tiny?*

Q: why no nuclei with mass > 7*?*

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: 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:

$\rightarrow$ measure lite elts and metals

low metallicity $\rightarrow$ more primitive

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

look for regions with low metallicity $\rightarrow$ 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

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

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

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

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{p} = (2.78 \pm 0.29) \times 10^{-5} \qquad (2)$$

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

$$\left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{\mathrm{QSOALS}} = \left(\frac{\mathrm{D}}{\mathrm{H}}\right)_{p} = (2.53 \pm 0.04) \times 10^{-5} \qquad (3)$$

now a 2% measurement!

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`

lite elts fit if η in range

$$3.4 \times 10^{-10} \leq \eta \leq 6.9 \times 10^{-10} \tag{4}$$

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