Astro 596/496 PC
Lecture 24
March 15, 2010

Announcements:

- PS4 due Friday in class

Last time: Big Bang Nucleosynthesis Theory and Observations

Q: compare/contrast BBN with CMB?

Q: BBN theory prediction(s)–qualitative, quantitative?

Q: how to test? challenges/complications?

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

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

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) $\rightarrow$ 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)

$$\left(\frac{\mathsf{D}}{\mathsf{H}}\right)_{\mathsf{QSOALS}} = \left(\frac{\mathsf{D}}{\mathsf{H}}\right)_p = (2.78 \pm 0.29) \times 10^{-5} \tag{2}$$

For the top 2 (multiple transitions)

$$\left(\frac{\mathsf{D}}{\mathsf{H}}\right)_{\mathsf{QSOALS}} = \left(\frac{\mathsf{D}}{\mathsf{H}}\right)_p = (2.49 \pm 0.18) \times 10^{-5} \tag{3}$$

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 $\rightarrow$ one value today

`www: Schramm plot`

Lite Elt Observations:

- measure 1 element: find η
- measure more elements: *each* picks an η

$\Rightarrow$ do inferred ηs 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

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

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

BBN Quantitative Results and Implications

Theory-Observation comparison

qualitatively: tests concordance, and hot big bang

if concordance found, then

quantitatively: measures cosmic baryon-to-photon ratio

Q: what baryons do, don't count? photons?

What's in a Number?

given η and, say, $T_0 \rightarrow n_{\gamma,0}$

Q: what else can we calculate?

Q: to what should these results be compared?

Q: implications of comparison

A Cosmic Baryon Census

BBN $\rightarrow$ baryon content of U.: "baryometer"
...just from lite elements
not by directly counting baryons today

From $\eta = n_B/n_\gamma$, and CMB $T_0 \rightarrow n_{\gamma,0}$, compute

- baryon number density

$n_{B,0} = \eta n_{\gamma,0} \sim 2.4 \times 10^{-7}$ baryons cm^{-3} ~ 1 baryon/cubic meter

- baryon mass density $\rho_{B,0} \approx m_p n_{B,0}$
- baryon density parameter $\Omega_B = \rho_B/\rho_{\text{crit}}$

$$0.024 \leq \Omega_B \leq 0.049$$

begs for comparison with

- other density parameters
- results of direct searches for baryonic matter

Subcritical Baryons and Two Kinds of Dark Matter

$$0.024 \leq \Omega_B \leq 0.049$$

$\Omega_{\mathrm{B}} \ll 1$

baryons do not close the universe!

$\Omega_{\mathrm{B}} \ll \Omega_{\mathrm{Matter}} \simeq 0.3$

most of cosmic matter is not made of baryons!

"non-baryonic dark matter"

huge implications for particle physics–more on this to come

Measure known baryons which are directly observable optically
i.e., in *luminous* form (stars, gas): $\rho_{\mathrm{lum}} = (M/L)_{\star}\,\mathcal{L}_{\mathrm{vis}}$

$\Omega_{\mathrm{lum}} \simeq 0.0024h^{-1} \sim 0.004 \ll \Omega_{\mathrm{B}}$

$\Rightarrow$ most *baryons* dark! **"baryonic dark matter"**

Q: Where are they?