Astro 507

Lecture 27

April 3, 2020

Announcements:

- **Preflight 5: due today**
- **Problem Set 5 due next Friday**

Last time: testing big-bang nucleosynthesis
naïvely seems easy, but it's not
Q: what are the BBN predictions we want to test?
Q: what's the complication? how do we proceed?

Testing BBN

Predictions: light element abundances

- large universal ^{4}He abundance: mass fraction $Y_p = \rho(^4\mathrm{He})/\rho_\mathrm{b} \sim 1/4$
- traces levels of D/H, ^{3}He/H, ^{7}Li/H

Seems easy–this is the composition of the Universe after ~ 3 min. Look anywhere!

But: can't observe until much later
once they emerge, *stars alter light element abundances*

Solution:
stars also make heavy element = "metals"
stellar cycling: metals $\leftrightarrow$ time
strategy: *measure light elements and metals*
low metallicity $\rightarrow$ more primitive
in limit of metals $\rightarrow$ 0: primordial abundances!

Assessing BBN: Theory vs Observations

(Standard) BBN theory has a free parameter: $n_B/n_\gamma = \eta$
different light 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 light elements: "overconstrained"

a priori η is unknown, but homogeneous U $\rightarrow$ one value today

`www: Schramm plot`

Light 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`

light elements fit if η in range

$$(6.143 \pm 0.190) \times 10^{-10} \qquad (1)$$

Have extrapolated hot big bang to $t \sim 1$ s

predict light elements $\rightarrow$ 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

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

- 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

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

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

baryons do not close the universe!

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

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): $\rho_{\rm lum} = (M/L)_{\star} \mathcal{L}_{\rm vis}$

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

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

Q: Where are they?

Where are the dark baryons?

• **compact objects** (white dwarfs, neutron stars, black holes)
search for *MACHOs*: MAssive COmpact Halo Objects
via gravitational microlensing
`www: lensing diagram, MACHO event`
see lensing events towards LMC!
but are they MACHOs or LMC stars? ...probably the latter

• **warm/hot intergalactic medium** (WHIM)
structure formation $\rightarrow$ infall $\rightarrow$ shock heat to $T \sim 10^5 - 10^7$ K
note: in galaxy clusters, most baryons in
hot "intracluster" gas, not galaxies!
`www: X-ray cluster`
but X-rays from WHIM gas harder to see...
recent evidence of diffuse "X-ray forest"
`www: Chandra spectra`

BBN and the CMB: Battle of the Baryons

Until recently:
BBN was the premier means for measuring $\eta \propto \Omega_B$
$\rightarrow$ the best cosmic "baryometer"

Now: CMB independently measures η

battle of the baryons
compare independent measures of η
test of cosmology!

If agreement: big bang working very well!
$z \sim 10^{10}$ theory & light elements
quantitatively consistent with $z \sim 10^{3}$ theory & CMB

If disagreement: a pressing problem!

BBN in Light of the CMB

Planck 2013:

$\Omega_{\text{baryon,CMB}} h^2 = 0.02207 \pm 0.00027$

$\Rightarrow \eta_{\text{CMB}} = (6.047 \pm 0.074) \times 10^{-10}$

- 1.2% precision!
- independent of BBN!

BBN vs CMB: Testing Cosmology

pillar vs pillar!

www: Schramm plot: η_{BBN} vs η_{CMB}

Concordance!

in more detail:

1. use η_{CMB} as input to (Std) BBN theory,
2. compute light elements
3. compare with observations

`www: abundance likelihoods (BDF, Olive, Yeh, & Young 2020)`

- D agreement perfect! ^{4}He agreement excellent
- ^{7}Li tension clearer – hot research topic
  "lithium problem" could point to new physics!

What's up with ^{7}Li?

- observational systematics (e.g., stellar parameters)? Quite possible.
  (Melendez & Ramirez 2004; FOV05)

- astrophysical systematics (e.g., depletion)? but what about ^{6}Li? and Li dispersion small ($\lesssim 0.2$ dex)...

- BBN calculation systematics: nuke reaction rates? But well-measured, and can use solar neutrinos to test dominant source: ^{3}He$(\alpha,\gamma)^7$Be (CFO04)

- new physics? if so, nature kind–didn't notice till now
  otherwise, would not have believed hot big bang...

Particle Dark Matter

BBN and Particle Dark Matter

BBN motivates dark matter theory & searches two ways:

Quantitative. $\Omega_B \ll \Omega_{\rm m}$: must have non-baryonic dark matter
...and lots of it!

Qualitative. BBN success at $t \sim 1$ s $\rightarrow$ early U as physics lab

"The universe is the poor man's particle accelerator"
– Ya. Zel'dovich

Big implications for–and motivations from–particle physics

Q: what can we say about DM properties generally?

Q: what can we say if DM is in particle form?
lifetime, mass, interactions, quantum #s?

Q: what known particles are candidates for non-baryonic DM?

Q: does particle theory offer dark matter candidates?

Elementary Particle Physics and Dark Matter

Dark matter

dark: no/feeble EM, strong interactions

matter: behaves as nonrelativistic material $\rightarrow \rho \propto a^{-3}$, $P \ll \rho c^2$

naturally leads to hypothesis of DM as

Weakly Interacting Massive Particles: **WIMPs**

If DM is swarms of WIMPs, what are their properties?

lifetime: must exist today $t_0 \sim 14$ Gyr

$\rightarrow$ stable or very long-lived

mass: don't know!

only know mass dens $\rho_{\mathrm{m},0}$ today on cosmic, galactic scales

but without also knowing # dens $n_{\mathrm{m},0}$, can't get $m = \rho/n$

$\rightarrow$ in fact, with specific model, from m get n_0

Could the Dark Matter be Neutrinos?

interactions/quantum #s:
BBN: dark matter not baryonic

Standard Model of particle physics *does* provide
a candidate for non-baryonic DM
stable + massive: neutrinos; can show (PS5):

$$\Omega_\nu h^2 = \frac{\sum_{\text{species}} m_\nu}{92 \text{ eV}} \tag{2}$$

...but can show (β decay, ν oscillations, CMB, LSS)
$\sum_{\text{species}} m_\nu \lesssim 1$ eV, and so

$$\Omega_\nu \sim 0.01 < \Omega_B \ll \Omega_{\text{m}} \tag{3}$$

we see: νs *are* non-baryonic DM
but *negligible contribution to density*
most dark matter is not neutrinos!

Q: other Standard Model candidates?

no other Standard Model particle candidates viable

non-baryonic DM demands physics beyond the Standard Model

particle candidates available "off the shelf"
in models of physics Beyond the Standard Model
i.e., particle physics models designed to explain
origin of standard model features

examples:
lightest supersymmetric particle, axion, strangelets...

Q: how are WIMPs produced in early U?