Astro 596/496 NPA

Lecture 21

March 8, 2019

Announcements:

- **Preflight 4** due today
- a bit of rest for the weary–*nothing due next Friday!*

Last time: BBN concordance and implications

- big bang cosmology working back to $t \sim 1$ sec, $z \sim 10^{10}$
  ...if we don't worry to much about lithium
- BBN measures Ω_B
  Q: what's that? Q: is it big or small–and compared to what?

Subcritical Baryons and Two Kinds of Dark Matter

$$0.039 \leq \Omega_B \leq 0.045$$

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

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

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

$\Rightarrow$ 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 2018:

$\Omega_{\rm baryon,CMB}h^2 = 0.02242 \pm 0.00014$

$\Rightarrow \eta_{\rm CMB} = (6.013 \pm 0.038) \times 10^{-10}$

- 1.2% precision!
- independent of BBN!

BBN vs CMB: Testing Cosmology

pillar vs pillar!

`www: Schramm plot:` $\eta_{\rm BBN}$ `vs` $\eta_{\rm CMB}$

Concordance!

BBN Theory/Data Confrontation

Procedure:

1. use $\eta_{\rm CMB}$ as input to (Standard) BBN theory

2. compute light elements
including uncertainties from nuke cross sections

3. compare with observations
including uncertainties

`www: abundance likelihoods (CFO)`

- D agreement perfect! ^{4}He agreement excellent–including $Y_{\rm CMB}$!
- ^{7}Li tension clearer – hot research topic
  lithium problem could point to new physics!

Q: how is lithium measured?

Lithium-7: Observations

best candidates: low-metal stars in our Galaxy
"population II" or "halo" or "spheroid" stars

old stars $\rightarrow$ low mass ($\sim 1 M_\odot$)
low metallicity: [Fe/H] < -1.5 down to -4

trouble: Li has low binding: "fragile"
burned when $T \gtrsim 2.5 \times 10^6$ K $\ll T_{\rm core,\odot}$
$\Rightarrow$ if surface material dragged into interior, can burn Li

stellar envelope convection $\rightarrow$ Li depletion
but: convection zone depth $\downarrow$ as $T_{\rm eff}$ $\uparrow$
$\Rightarrow$ pick hottest $\gtrsim 5800$ K (MS, subgiants)
no (?) Li depletion

measure Li I via absorption

`www: solar spectrum around 6707Å`

`www: halo star spectra`

^{7}Li Results

Spite & Spite (1984): first Li in Pop II

- $(\mathrm{LI/H})_{\mathrm{II}} \sim 10^{-10}$
- Li flat at low [Fe/H]: "Spite plateau"

$\star$ if undepleted $\rightarrow$ primordial!

Plateau data:

`www: Li vs Fe`

$$\left(\frac{\mathrm{Li}}{\mathrm{H}}\right)_p = (1.23 \pm 0.06^{+0.60}_{0.40}) \times 10^{-10} \qquad (1)$$

statistical errors: many stars $\rightarrow$ small

systematics: dominate

- ± 0.40 due to stellar atmosphere modelling
- $+0.30$ due to possible Li burning (depletion) constrained by observations of fragile ^{6}Li

What's up with ^{7}Li?

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

- astrophysical systematics (e.g., depletion)?
  but interstellar Li in Small Mag. Cloud agrees with stellar abundance!
  and for much of plateau, Li dispersion small ($\lesssim 0.2$ dex)
  but at [Fe/H] $\lesssim -3$] large dispersion: "plateau meltdown"
  $\rightarrow$ at least some stars eat Li! But why the metal dependence?

- 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...