Astro 350

Lecture 35

Nov. 16, 2011

Announcements:

- HW10 due next time
- Discussion Question 10 due today

Last time:

- CMB summary–big bang works well back to $t = 400,000$ years
- press on to even earlier times: 1 second!
- strategy: extrapolate using known properties of matter

The Cosmic Nuclear Age

in early Universe, strong/nuclear force important

Q: what were cosmic ingredients then?

Q: what transition(s) expected?

Q: what physical effects important? cosmo? microphysical?

Q: what fossils might be left over?

Q: how could we observe them?

Hint: States of Matter

matter state	basic ingredient	approximate temperature
neutral gas, liquid, solid	neutral atoms and molecules	$T \lesssim few \times$ 1000 K
ionized gas: plasma	free electrons, ions=nuclei	$few \times$ 1000 K $\lesssim$ T $\lesssim 10^{10}$ K
"nucleon plasma"	free electrons, free "nucleons" n, p	$T \gtrsim 10^{10} K$

Primordial Nucleosynthesis

Primordial nucleosynthesis, a.k.a. Big bang nucleosynthesis (BBN):
production of lightest elements H, He, Li
in the early U.

extrapolate expanding U w/ matter, radiation
back to $t \sim 1$ sec $\rightarrow$ U is giant nuke reactor!

basic story:
transition from "ionized" free n and p
to "neutral" bound nuclei, largely ^{4}He

Primordial Nucleosynthesis Initial Conditions

time $t < 1$ sec, temp $T > 10^{10}$ K $=$ 10 billion degrees

radiation

- "CMB" photons now gamma rays!
- also a sea of cosmic neutrinos!

radiation density huge! $\rho_{\text{radiation}} \gg \rho_{\text{matter}}$ opposite of situation today

"radiation-dominated era"

matter

- ordinary (known) matter: only n, p, and e
  collisions too violent for complex nuclei
  and certainly much too violent for atoms
- dark matter: must be around, but weakly interacting

dark energy

must also be around, but if Λ-like, unimportant

iClicker Poll: Cosmic Fusion

primordial nuke: transition from free n, p
to bound nuclei, through a series (chain) of reactions

Starting from p and n only, which nucleus is made first?

A deuterium: $d = \boxed{np}$

B helium-3: $^3\text{He} = \boxed{npp}$

C helium-4: $^4\text{He} = \boxed{nnpp}$

D lithium-7: $^7\text{Li} = \boxed{3p, 4n}$

Primordial Nucleosynthesis: Element Production

as the universe expands and cools,
n and p collisions weaker than $d = \boxed{np}$ binding
$\rightarrow$ at last d can survive: $n + p \rightarrow d$
then can combine d with n, p, and d to make heavier things
`www: reaction network`

flow $\rightarrow$ most stable (tightest binding) = $\boxed{{}^4\text{He}}$
essentially all $n \rightarrow {}^4$He
BBN result: 24% of baryons in He, leftover $p \rightarrow$ H (76%)
small traces of unburnt D, ^{3}He, ^{7}Li:
amounts depend strongly on density of nuclei ("baryons")
`www: Schramm plot`

Nothing heavier than lithium made–why?

Nuclear Freeze

nothing heavier than Li:

- no stable nuclei with masses $5, 8$
  $\Rightarrow$ don't make anything from $p + {}^4\text{He}$ or ${}^4\text{He} + {}^4\text{He}$

- cooling universe $\rightarrow$ weaker collisions
  but combining nuclei with large charge
  requires large energy to overcome electrical repulsion

result: nuclear reactions shut down after lithium production
...and not even much of that!
"freezeout of strong interactions"

BBN Predictions: Executive Summary

Q: what are main predictions? qualitatively, quantitatively?

Q: where, when do they apply?

Q: what predictions "robust"/unavoidable?

Q: what would be involved in testing the predictions?

Q: what would it mean if BBN predictions confirmed? if not?

Q: what assumptions went into the calculation? ("Standard BBN")

Q: i.e., regarding dark matter? dark energy? neutrinos? additional element ary particles?

BBN: Observations

to test BBN: measure primordial abundances

look around the room–not 75% H, 25% He.
Q: is this a problem? Why not?

matter in solar system: mostly in Sun–mostly H, then He
but: still have heavy elements
Q: is this a problem? Why not?

Q: so how test BBN? What is the key practical issue?
Q: when in cosmic history do we expect
the first "complications"?

BBN: Observations–Idealized

`The past isn't dead.  It isn't even past.`
`  -- Cosmologist William Faulkner`

BBN theory: after the first three minutes
the universe filled homogeneously with
H, He, and a little Li
$\rightarrow$ these remain to this day as "fossils"
of nuclear reactions in the early universe
$\rightarrow$ evidence from the early U is all around us!

BBN: Observations–Hard Reality

BBN theory: universal composition after ~ 3 minutes, $z \sim 10^9$
observations: abundances in real astro systems, redshifts $z \sim few$

the first non-BBN nucleosynthetic processing:
$\rightarrow$ when first stars turn on
`www: circle of life`

problem: stars change lite elt abundances $\rightarrow$ "pollution"

the solution:
Q: how to address this problem?
Q: if can measure abundances in a system, can you unambiguously tell that stars have done some polluting?
Q: how to tell observationally which systems least polluted?

stars also make heavy elements

stellar cycling: $\boxed{\text{metals} \leftrightarrow \text{time}}$

$\rightarrow$ measure lite elts and **metals**

low metallicity $\rightarrow$ more primitive

at 0 metals $\rightarrow$ primordial

Helium-4

He atoms: tightly bound atoms, hard to excite electrons
$\rightarrow$ need relatively high energies to make observable lines
$\rightarrow$ need hot environment with strong collisions
$\rightarrow$ superheated gas in environment of massive, hot stars

need hot, metal poor gas:
$\rightarrow$ metal-poor, dwarf irregular galaxies
`www: I Zw 18`
Transp: *He emission lines*

$Y = \rho(^4\text{He})/\rho_{\text{baryon}}$ and $Z = \rho(\text{metals})/\rho_{\text{baryon}}$
$\Rightarrow$ correlated
What correlation do you expect?

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

Helium-4 Data: Trends and Implications

Data best fit by

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

slope $\Delta Y/\Delta Z$: stellar nuke

(avg stellar "helium per metal" output)

intercept $Y_0 = Y_p$: cosmology (primordial He!)

combining all data: infer primordial abundance

$$Y_p = 0.249 \pm 0.009 \qquad (2)$$

i.e., observe 24.9% of ordinary (baryon) mass to be in ^{4}He

Assessing BBN: Theory vs Observations

BBN Theory:

all elements depend on baryon density

only free parameter in standard ("vanilla") calculation

$\Rightarrow$ for each ρ_{B} value, 4 lite elements

"overconstrained"

at any moment, how many values of ρ_{B} in U?

Transp: *Schramm plot*

Lite Elt Observations:

1 element: find ρ_{B}

more elts: each picks an ρ_{B}

$\Rightarrow$ do they agree? test of BBN!

Combine observations (+ errors!)
observed light elements agree with theory (and each other!)
if $\Omega_{\mathrm{B}} = \rho_{\mathrm{B}}/rho_{\mathrm{crit}}$ in range

$$0.024 \lesssim \Omega_{\mathrm{B}} \lesssim 0.050 \tag{3}$$

recap: extrapolated big bang to $t = 1$ s, predicted lite elts
kinda amazing: not only qualitative agreement (“lotsa helium”)
but even detailed quantitative agreement with observations!
Cosmo bragging rights: BBN is earliest probe!

BBN: Implications

Qualitatively

extrapolated big bang to $t = 1$ s

predicted lite elts $\rightarrow$ agreement with observations

big bang working well back to 1 sec!

Quantitatively

observed lite elements select $\eta = n_B/n_\gamma$

$\Rightarrow 0.024 \lesssim \Omega_\mathrm{B} \lesssim 0.050$

1. $\Omega_\mathrm{B} \ll 1$: baryons don't close the U.

2. $\Omega_\mathrm{lum} \sim 0.007 \ll \Omega_\mathrm{B}$

baryonic dark matter hot (10^{6-7} K) intergalactic gas?

3. $\Omega_{\rm matter} \approx 0.3 \gg \Omega_B$:

non-baryonic dark matter

Also: BBN sensitive to particle physics

The universe is the poor man's particle accelerator.