Astro 350

Lecture 35

Nov. 28, 2012

Announcements:

- **Discussion 10** due today
- **Discussion 11** – last one! Due next Wednesday
- **Homework 10** due Friday at start of class

Last time: origin of the elements–primordial nucleosynthesis

Q: primordial? nucleosynthesis?

Q: what's the twitter/text message version of what happens?

Primordial Nucleosynthesis: Executive Summary

Big Bang Nuke: *a love story*

- begin at early times and high density, temperature
  with a "soup" of protons p and neutrons n

- neutrons much less common: 7p for each n
  environment too hostile for love–lonely and sad :(

- but as the Universe cools, binding becomes possible
  $\rightarrow$ p meets n! sparks fly!

- p and n get together, and make elements
  mostly ^{4}He $=$ $\boxed{2n + 2p}$: "favorite" p+n combo
  $\rightarrow$ n and p "prefer" to be in ^{4}He if possible
  also traces of deuterium, lithium leftover

- but still some cosmic sadness
  some p "remain single," leftover to be hydrogen today

iClicker Poll: Neutron/Proton Equality

Main effect of BBN: ^{4}He production

n and p "prefer" to be in ^{4}He if possible

very tightly bound = stable nucleus

Imagine:

- initially *equal* amounts of n and p, i.e., $n/p = 1$

What elements will ultimately be produced and remain today?

A only hydrogen an no helium

B only helium and no hydrogen

C some helium and some hydrogen

The Cosmic Neutron Dance

• if p for every n, so that $n/p = 1$
then every pair of p can find a pair of n
and make ^{4}He, with *no p leftover*
$\rightarrow$ result is baryons are 100% ^{4}He, 0% H
$\rightarrow$ not our universe! stars with *fewer* n than p

• now what if 2 p for every n, so that $n/p = 1/2$?
Q: how much ^{4}He*? leftover H?*

• now what if 7 p for every n, so that $n/p = 1/7$?
Q: how much ^{4}He*? leftover H?*

Q: what's the lesson?

• if 2 p for every n, so that $n/p = 1/2$
then for every pair of n, there are $4p$
make ^{4}He, with *2 p leftover* for each
→ result is 2 p (total mass 2) for every ^{4}He (mass 4), and so
→ baryons are 66% ^{4}He by mass, 33% H
→ still not our universe!

• our Universe: $7p$ for every n, so that $n/p = 1/7$
then for every pair of n, there are $14p$
make ^{4}He, with *12 p leftover* for each
→ result is 12 p (total mass 12) for every ^{4}He (mass 4), and so
→ baryons are 25% ^{4}He by mass, 75% H

Lesson: ^{4}He set by n/p ratio!

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

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

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

$$Y_p = 0.249 \pm 0.009 \tag{2}$$

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

Assessing BBN: Theory vs Observations

BBN Theory:

- always get about 25% helium, 75% hydrogen

$\rightarrow$ amounts are nearly *independent* of
amount (density) of baryons in the Universe

- but the trace amounts of deuterium and lithium (and ^{3}He) *do* depend strongly on baryon density ρ_B

So: can measure amount of deuterium
and this *tells us* the density of baryons
$\rightarrow$ that is, deuterium "measures" the amount of
ordinary matter in the Universe!

Deuterium (and helium) tell us that if $\Omega_{\rm B} = \rho_{\rm B}/\rho_{\rm crit}$ in range

$$0.040 \lesssim \Omega_{\rm B} \lesssim 0.050 \tag{3}$$

$\rightarrow$ baryon density is 4% to 5% of critical density

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 baryon density

$\Rightarrow 0.040 \lesssim \Omega_{\rm B} \lesssim 0.050$

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

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

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

3. $\Omega_{\text{matter}} \approx 0.3 \gg \Omega_{\text{B}}$:

non-baryonic dark matter

confirms: **most dark matter** is **not**
made of atoms of any kind in any arrangement!
$\rightarrow$ must be exotic form of matter!

known matter = anything on the periodic table
is a tiny fraction of the makeup of the cosmos!