Astro 406

Lecture 36

Nov. 20, 2013

Announcements:

- **PS 11 due now**
- **PS 12 due Friday after break** last problem set!

Last time:

- finished CMB: the atomic age
  big bang working well back to $t = 400,000$ yr
- pressed back to the nuclear age
  Q: why don't nuclei fly apart?
  Q: characteristic nuclear energy scale?
- fun nuclear fact:
  no nuclei have $A = 5$ or 8 neutrons + protons *Q: why?*

The Cosmic Nuclear Age

in early Universe, strong/nuclear force important

Q: to zeroth order, when is epoch?

Q: what what universe like then? environment, particles?

Q: what transition(s) expected?

Q: what fossils might be left over?

Q: how could we observe them?

Primordial Nucleosynthesis

Big bang nucleosynthesis (BBN): production of lightest elements H, He, Li in the early Universe

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

1950's: George Gamow
since early U. very dense
Q: what is densest object not a black hole?
$\rightarrow$ all neutrons
expand: $n \rightarrow p + e^- + \bar{\nu}_e$ decay
$n + p \rightarrow$ *all elements made in first cosmic seconds!*
`www:` $\alpha\beta\gamma$ `paper`

Q: what flaw(s) in argument?

Enrico Fermi:

big bang can't make all elements

no stable nuclei with $n + p = 5, 8$ particles

mass "gaps" stop flow

C. Hayashi:

weak interactions (neutrinos) important

initial baryon state *not* just neutrons!

Q: why? what is effect of energetic neutrinos?

Note:

when $kT \sim$ MeV $\sim$ nuke binding

Q: are baryons (n, p) relativistic or not?

BBN: Theory

want to predict element "cooking"

Recipe:

follow weak, nuclear reactions
in expanding, cooling U.

The Oven: radiation dominated universe
$a^2 \propto t$, but since $T \propto 1/a$
$t \propto 1/T^2$

$$t = \left(\frac{1 \text{ MeV}}{kT}\right)^2 \text{ 1 s} \tag{1}$$

so $kT = 1$ MeV $\rightarrow T \simeq 10^{10}$ K at $t \simeq 1$ s
Q: what is central temperature of Sun?
$kT \gg$ atom biding energy $\rightarrow$ U. ionized

Nucleosynthesis: Ingredients

radiation:
initially, $kT > m_e c^2 = 0.5$ MeV$, m_\nu c^2$
Q: so what does this mean? what is radiation?
$\rightarrow \gamma, e^\pm, \nu\bar{\nu}$ (3 species) relativistic
CMB now gamma rays!

matter: $kT \ll m_p c^2, m_n c^2 \simeq 1000$ MeV
n, p non-rel; assume DM is too
also: since nuclear binding $\sim$ MeV, nuclei "ionized" too
$\rightarrow n, p$ only, no complex nuclei

key parameter: $n_{\text{baryon}}/n_\gamma \equiv \eta$
don't know yet, will solve for it
preview: $\eta \sim 10^{-9}$
$\Rightarrow$ billions of photons for every baryon!

Q: which complex nucleus will be the first to form?

BBN: Plot Summary*

to build nuclei, first step is
$n + p \rightarrow \boxed{np} = d + \gamma$ *deuterium*
but $n_\gamma \gg n_B$: $\gamma + d \rightarrow n + p$ can occur

D destroyed as soon as made $\rightarrow$ can't form nuclei
"deuterium bottleneck"

Q: when bottleneck overcome?
then nuke reactions $\rightarrow$ nuclei

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*simplified version

iClicker Poll: Cosmic Nucleosynthesis

Vote your conscience!

At $t = 1$ sec and $T \sim 1$ MeV
Cosmic baryons are n and p in the ratio $n/p \approx 1/7$

When nuclear reactions start, what will be the main endproduct?

A hydrogen

B ^{4}He

C iron

D uranium

The Origin of Species

$kT \sim 0.1$ MeV, $t \sim 100$ s
now photons too feeble to destroy D
elements build rapidly
`www: rxn network`

flow $\rightarrow$ most stable (tightest binding) = ^{4}He
essentially all $n \rightarrow {}^{4}$He

BBN results:

- 24% of baryonic mass into helium-4
- leftover 76%: $p \rightarrow$ hydrogen
- small traces of unburnt D, ^{3}He, ^{7}Li:
  amounts depend strongly on η

`www: Schramm plot of BBN predictions`

Q: why do you think D drops with η, i.e., with more baryons?

Q: why nothing heavier than lithium? why not Fe or U?

Nuclear Freeze

BBN makes nothing heavier than Li

the most abundant species are p and ^{4}He

- combining them would make $\boxed{pp = {}^2\text{He}}$, $\boxed{p\,{}^4\text{He} = {}^5\text{Li}}$, or $\boxed{{}^4\text{He}\,{}^4\text{He} = {}^8\text{Be}}$
- but ^{2}He is *unstable*, as is any *mass 5 or 8* nucleus

$\Rightarrow$ can't make anything new with 2-body reactions

expanding, cooling U. $\rightarrow$ reactions rarer, less energetic with time

- fewer chances to react at all
- Coulomb repulsion of nuclei $\rightarrow$ shuts off nuke rxs at low T

$\Rightarrow$ *"freezeout of strong interactions"*

iClicker Poll: The ASTR406 Diaspora

No class next week–Thanksgiving break

How far will you be from this spot one week from now?

A < 3 miles

B 3 to 30 miles

C 30 to 300 miles

D 300 to 3000 miles

E > 3000 miles